

Thermal environment and heat transmission



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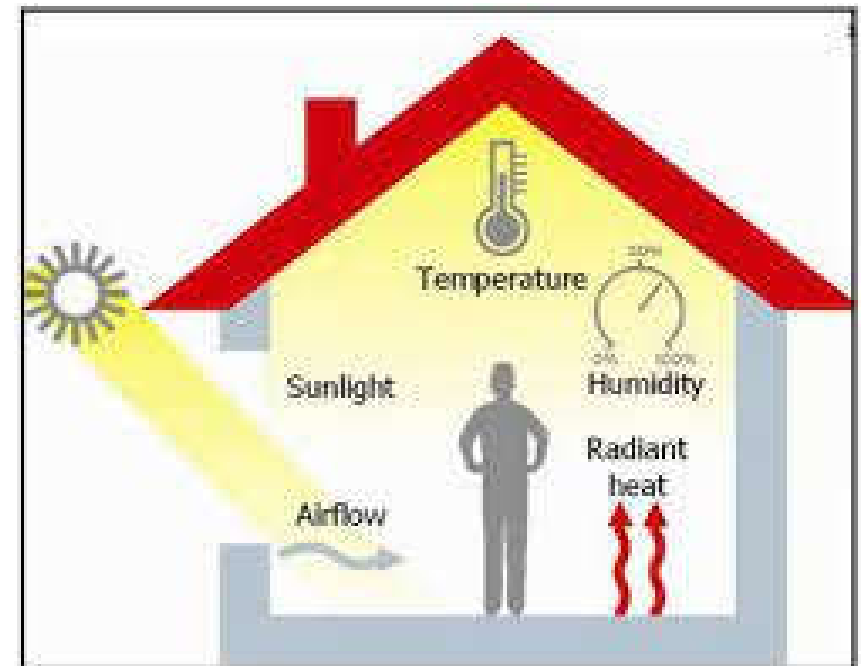
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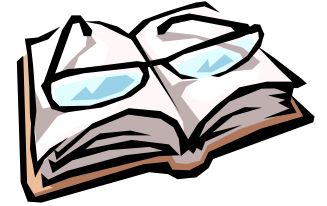
Contents



- Basic concepts
- Thermal behaviour of buildings
- Passive building design
- Solar control
- Dynamic simulation



Basic concepts



- Physics of heat
 - Heat and temperature ($^{\circ}\text{C}$ or K)
 - Specific heat ($\text{J}/\text{kg}\cdot\text{K}$) & latent heat (kJ/kg)
 - Heat flow rate, Q (J/s or W)
 - Heat flux density (W/m^2)
- Heat flow
 - Density (kg/m^3), conductivity ($\text{W}/\text{m}\cdot\text{K}$)
 - Heat loss: the U-value [$Q = U A \Delta T$]
 - Convection coefficient h_c , reflectance/emittance

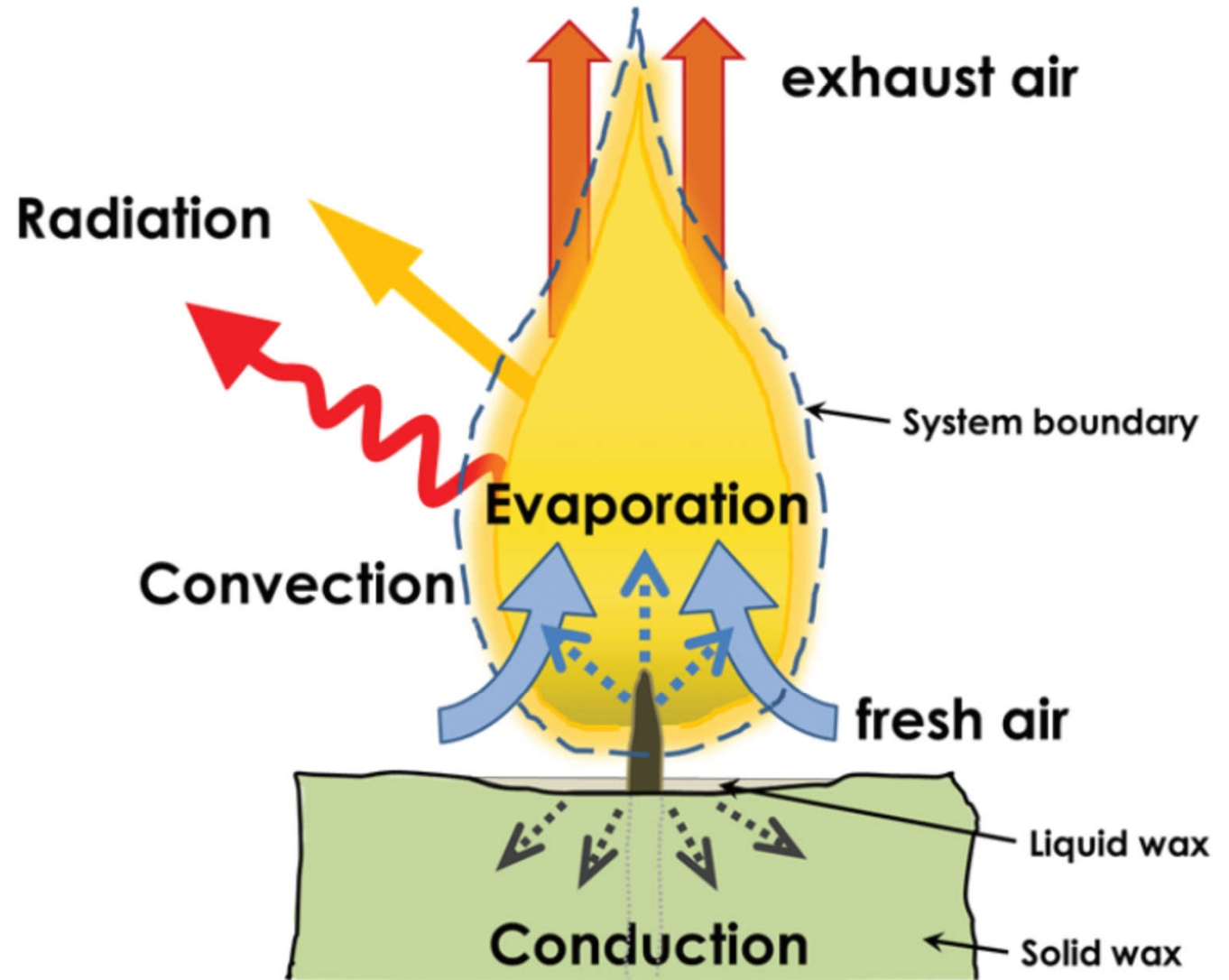


HEAT



TEMPERATURE

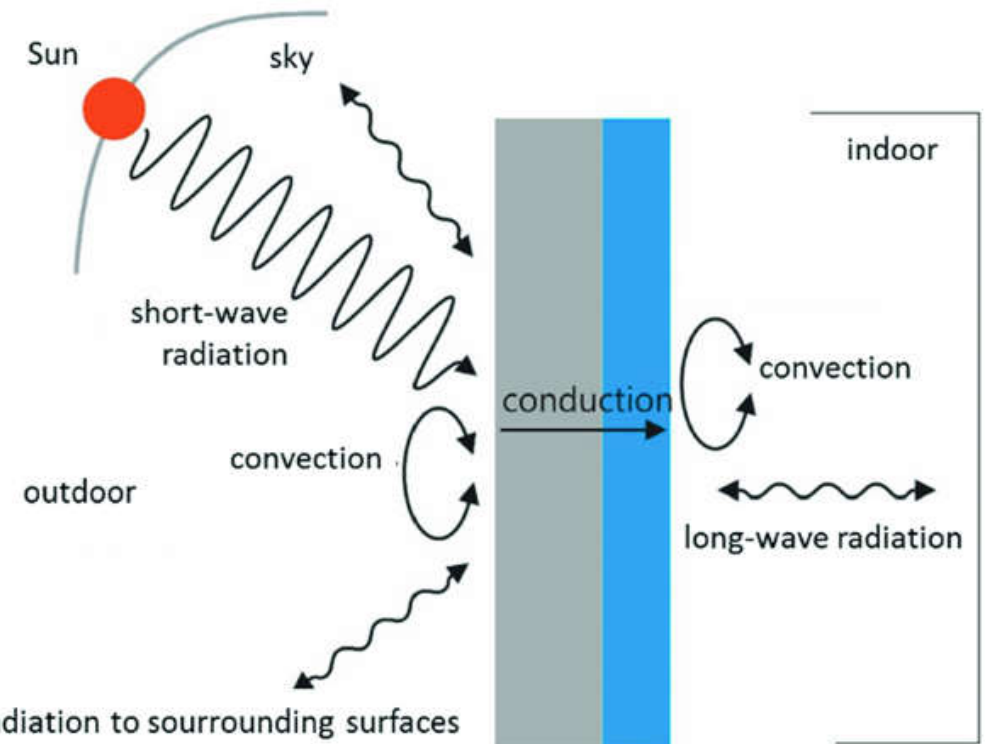
A candle transferring heat into its environment by radiation, convection, evaporation and conduction





Basic concepts

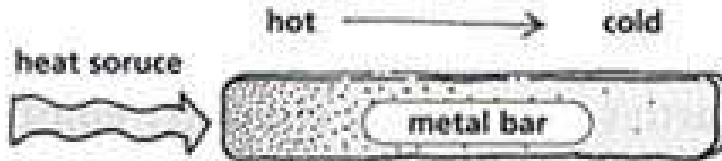
- **Thermal environment** refers to the things that can affect heat transfer at that point
- Mechanisms of heat transfer:
 - Conduction
 - Convection (sensible)
 - Radiation
 - Phase change (latent)



Four forms of heat transfer

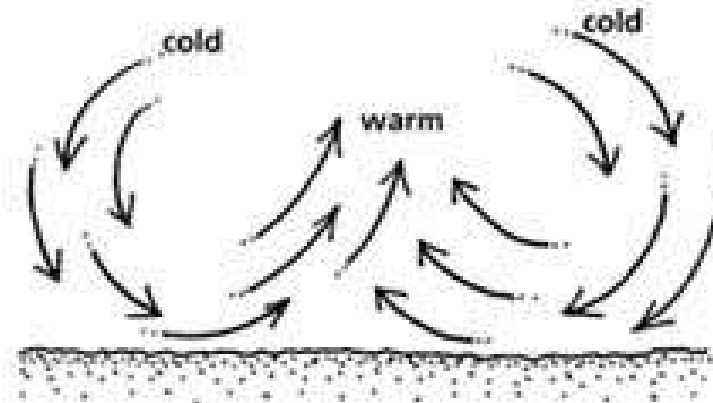
CONDUCTION

From molecule to molecule



SENSIBLE HEAT

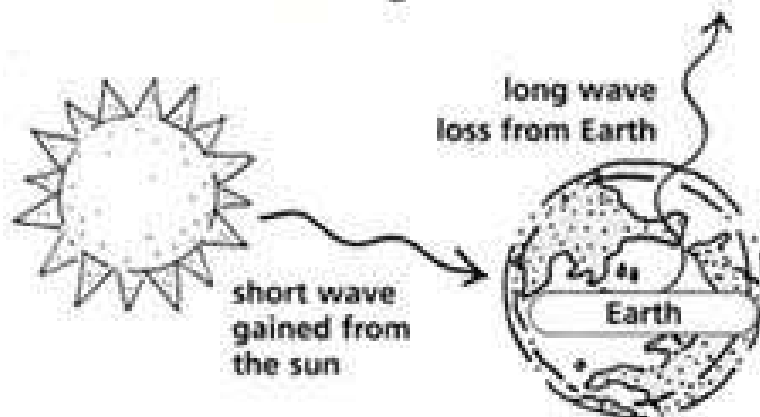
Fluid movement of heated air



CONVECTION

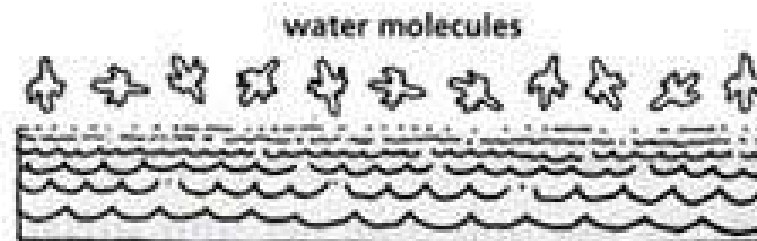
RADIATION

Energy passing from one object to another without a connecting medium

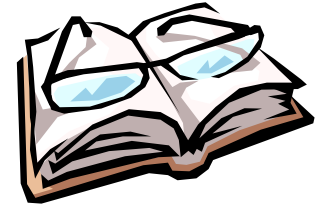


LATENT HEAT

Chemical energy due to water phase changes (evaporation, condensation, etc.) and water vapour transfer

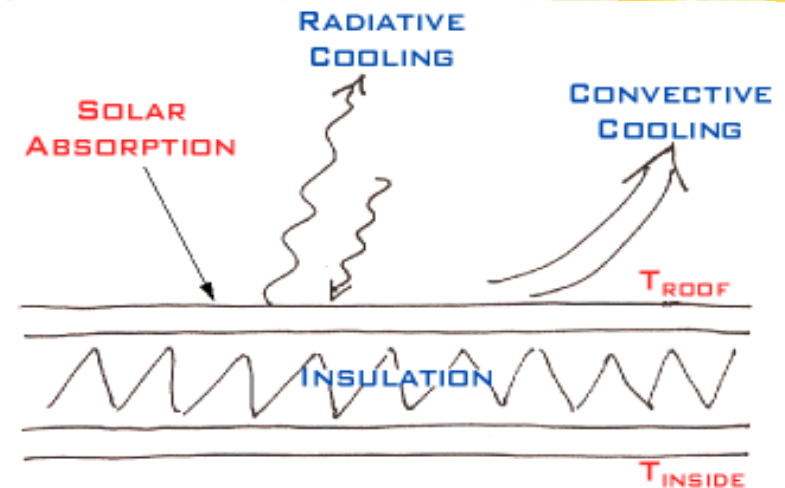


Basic concepts



- Heat transfer mechanism

- Conduction
- Convection
- Radiation



$$Q_{IN} = U \cdot (T_{ROOF} - T_{INSIDE})$$

- Thermal properties of building materials

- Overall thermal transmittance (U-value)
- Thermal conductivity
- Thermal capacity (specific heat)

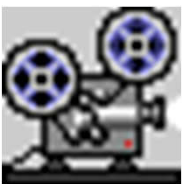
$$Q = U A (\Delta t)$$

Typical properties of selected materials

<i>Material</i>	<i>Density (kg/m³)</i>	<i>Thermal conductivity (W/m K)</i>	<i>Specific heat capacity (J/kg K)</i>
Bricks	1700	0.73 ^a	800
Concrete, dense	2000	1.13	1000
Glass fibre quilt	25	0.035	1000
Asphalt	1700	0.50	1000
Aluminium	2700	214	920
Water (20 °C)	1000	0.60	4187
Sand (dry)	1500	0.30	800
Steel	7800	45	480
Wood	500–700 ^b	0.12–0.23 ^b	1200–3400 ^b

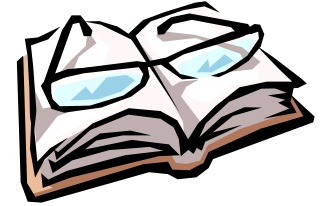
^a Mean of internal and external brick types. Consult manufacturers' data for precise values.

^b Values vary depending on wood type, temperature and water content.



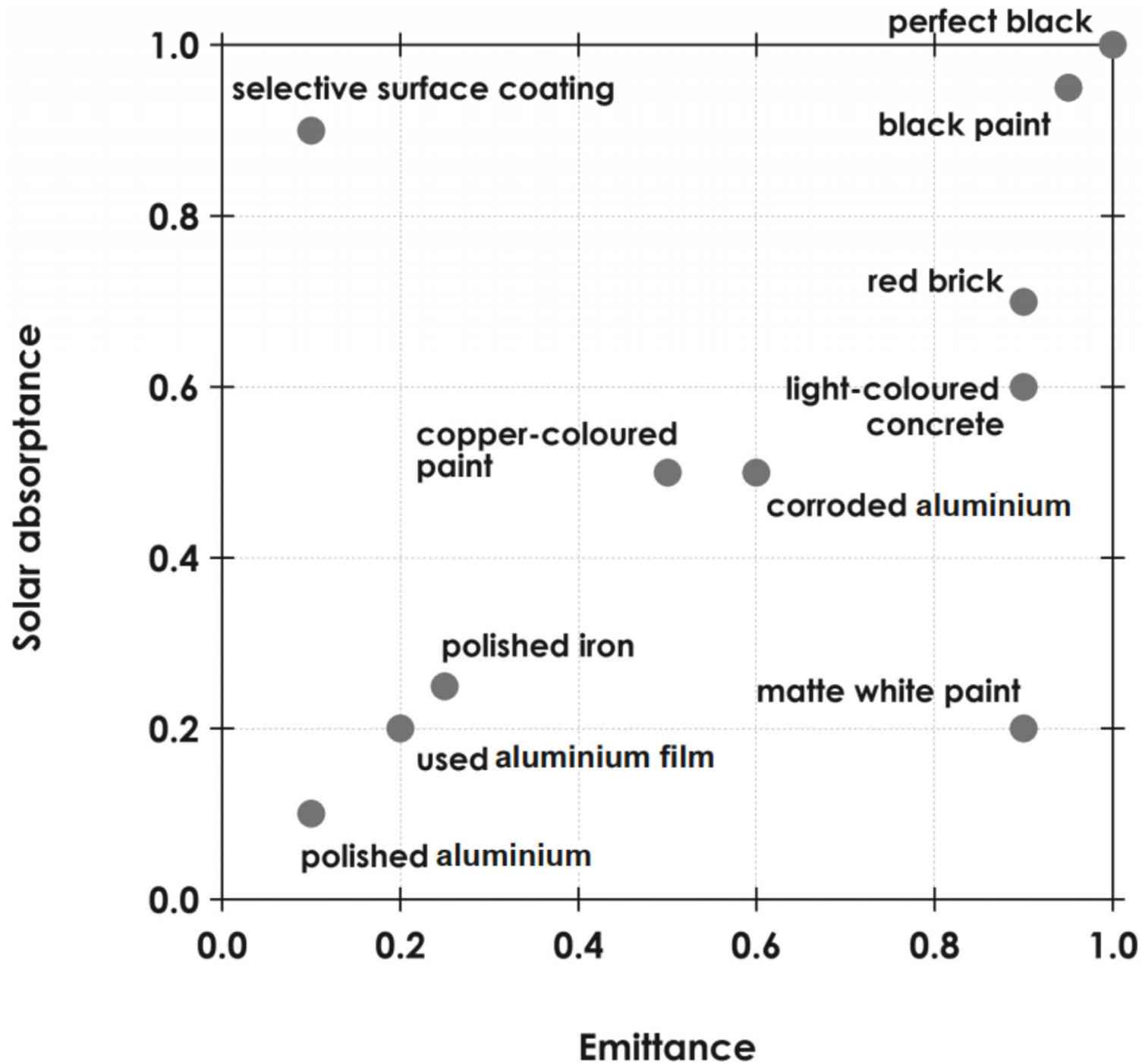
Video: Thermal Properties of Building Materials (5:52) <https://youtu.be/ch0d5Hb-qA>

Basic concepts



- **Emittance** (or emissive power)
 - It is the total amount of thermal energy emitted per unit area per unit time for all possible wavelengths
- **Emissivity** of a body at a given temperature
 - It is the ratio of the total emissive power of a body to the total emissive power of a perfectly black body at that temperature
- **Solar absorptance**
 - It is the proportion of the total incident solar radiation that is absorbed by the material (the remainder is reflected)

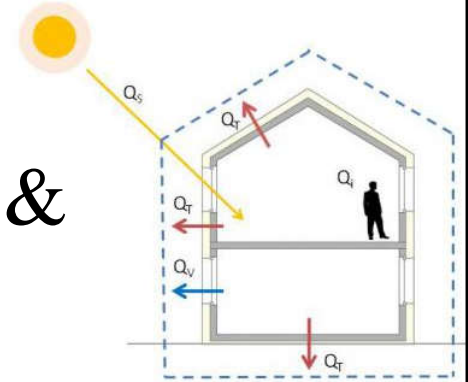
Emittance versus solar absorptance of some building materials



Basic concepts



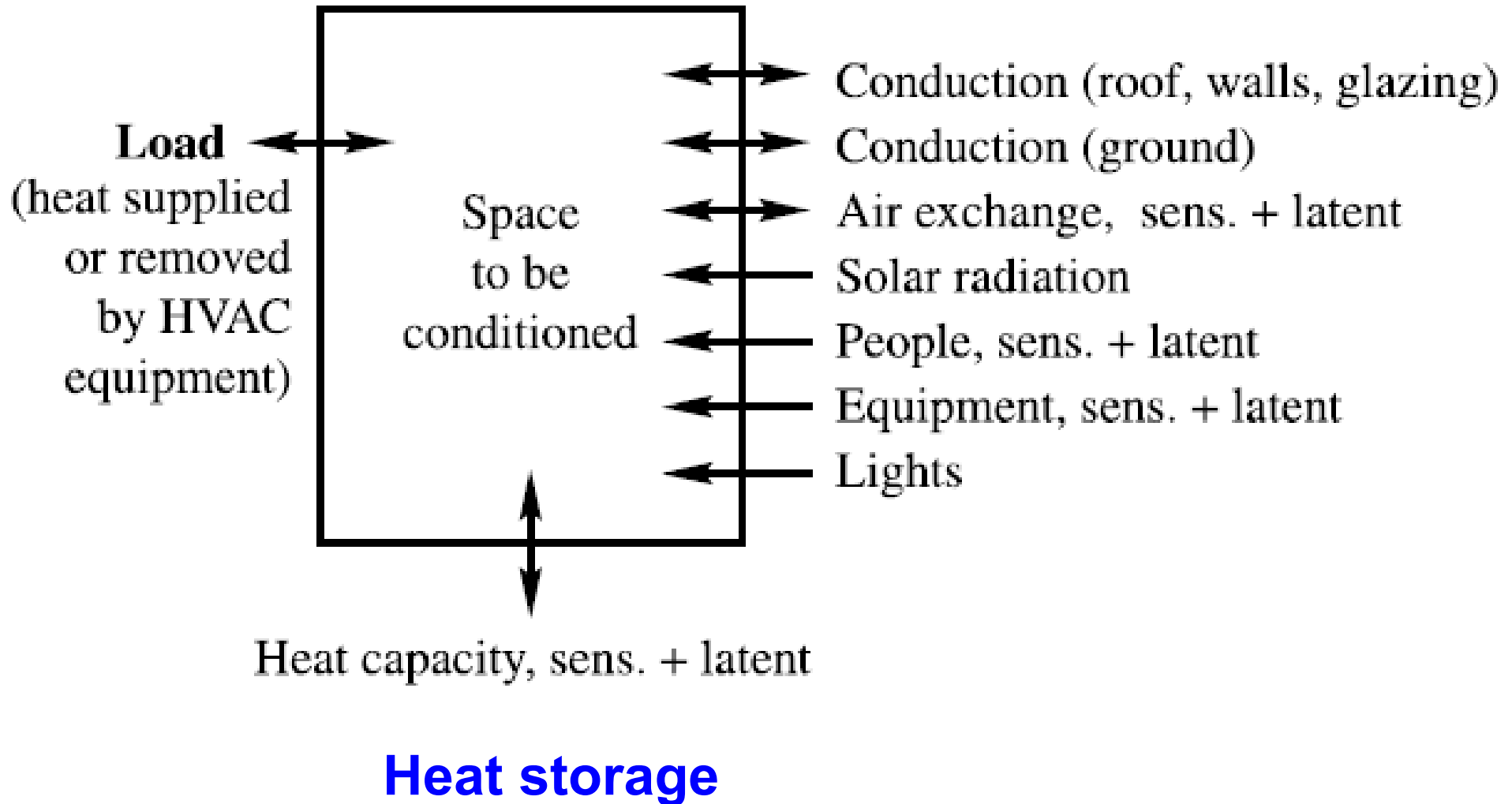
- **Thermal transmission in buildings**
 - External walls, windows, roof, doors and floors
 - Insulation (thermal) to reduce the heat transfer
 - Ventilation (infiltration & exfiltration)
 - Thermal properties of building materials & construction components
 - Determining U values for real building elements
 - <https://www.cibsejournal.com/cpd/modules/2011-06/>



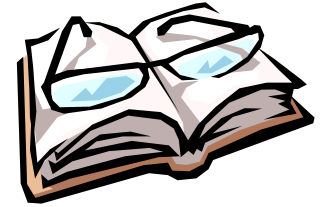
Thermal load, heat gains/losses & heat storage

Thermal Load

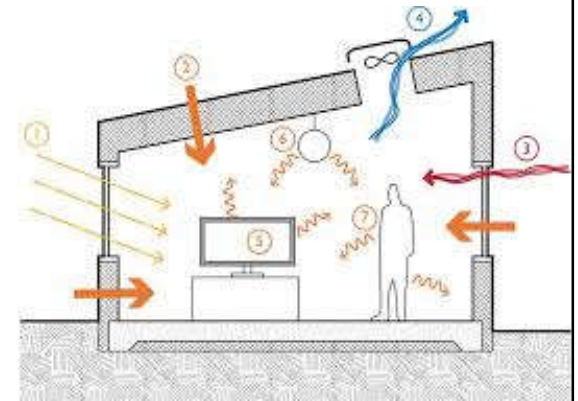
Heat Gains/Losses



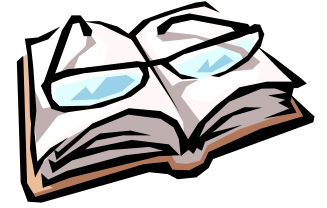
Basic concepts



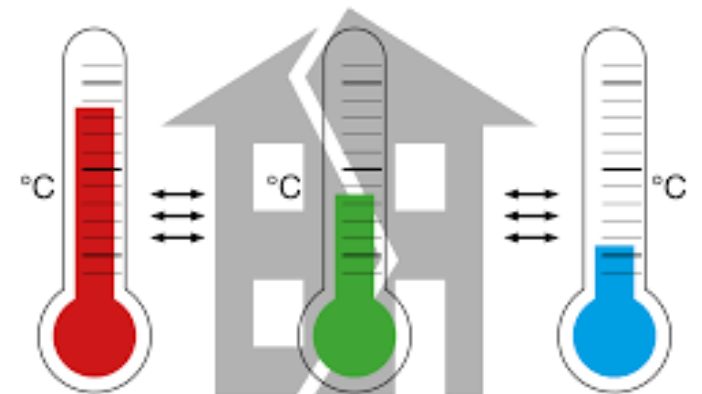
- Calculating heat gains (or losses)
 - Heat gain through external walls
 - Heat gain through roof
 - Solar heat gain through window glass
 - Conduction heat through window glass
 - Internal heat gains
 - Ventilation and/or infiltration heat gains
 - Latent heat gains (moisture transfer/generation)



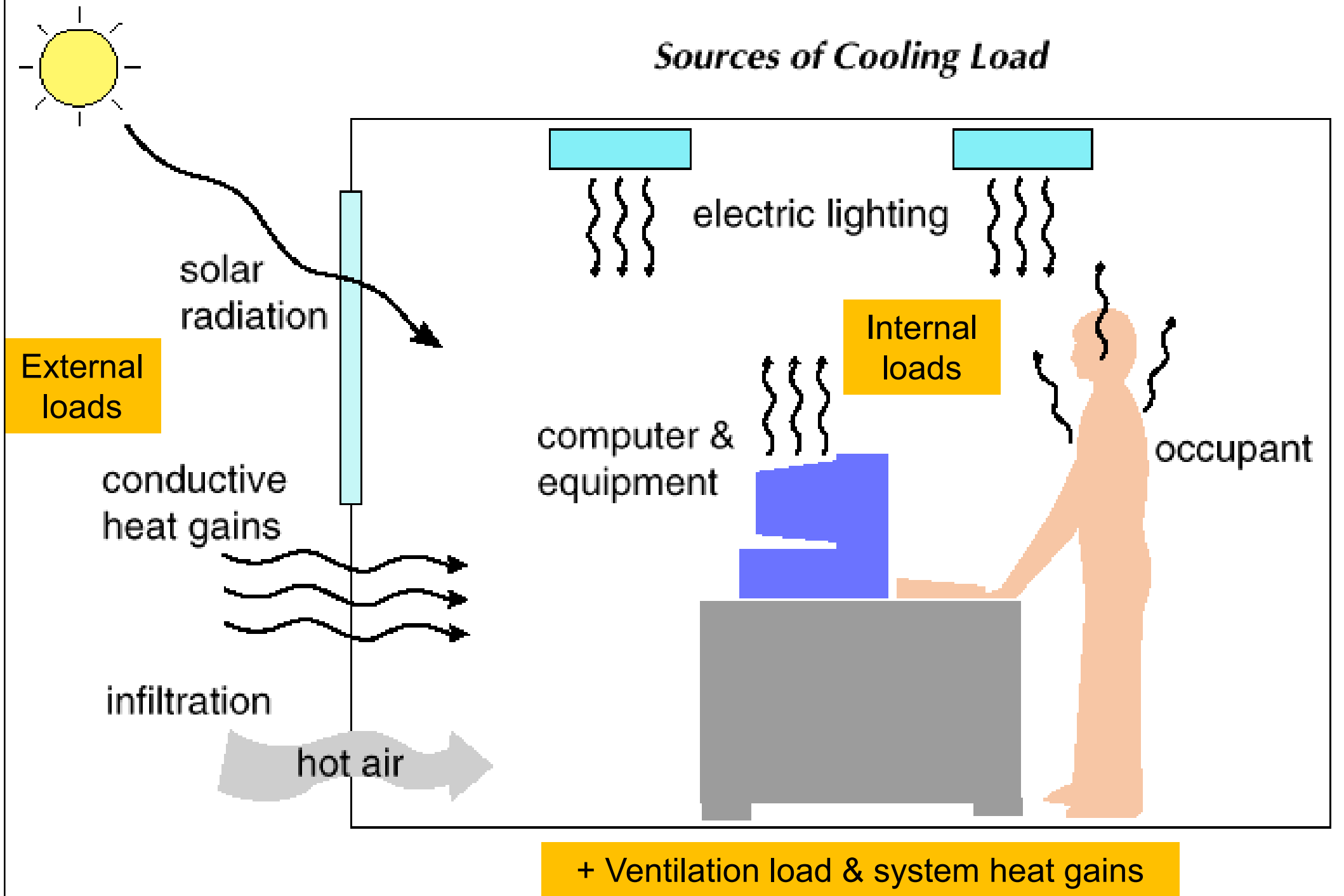
Basic concepts



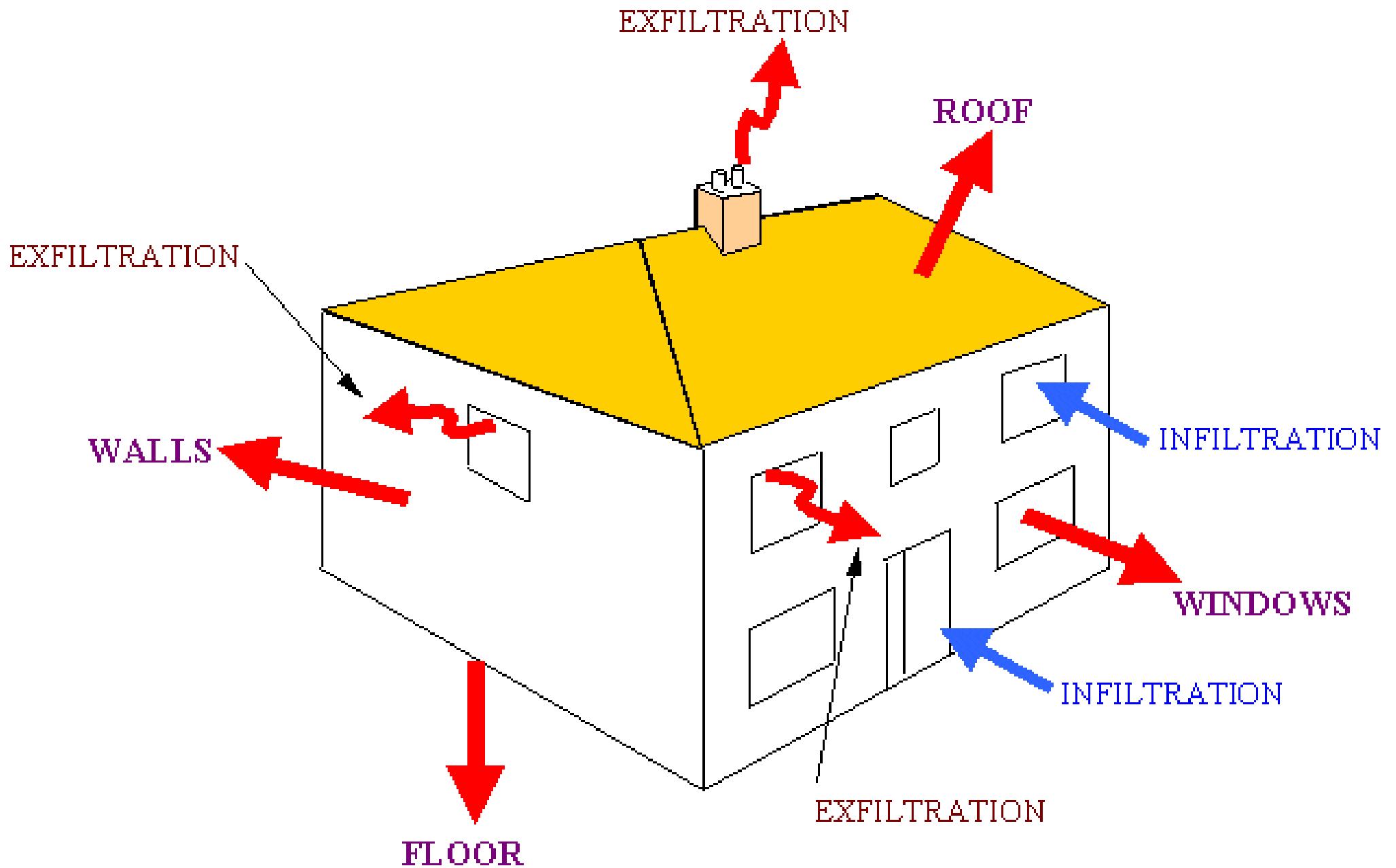
- Heat transfer basic relationships (for air at sea level) (SI units)
 - Sensible heat transfer rate:
 - $q_{\text{sensible}} = 1.23 \text{ (Flow rate, L/s)} (\Delta t)$
 - Latent heat transfer rate:
 - $q_{\text{latent}} = 3010 \text{ (Flow rate, L/s)} (\Delta w)$
 - Total heat transfer rate:
 - $q_{\text{total}} = 1.2 \text{ (Flow rate, L/s)} (\Delta h)$
 - $q_{\text{total}} = q_{\text{sensible}} + q_{\text{latent}}$



Components of building cooling load



Heat losses for heating load calculation

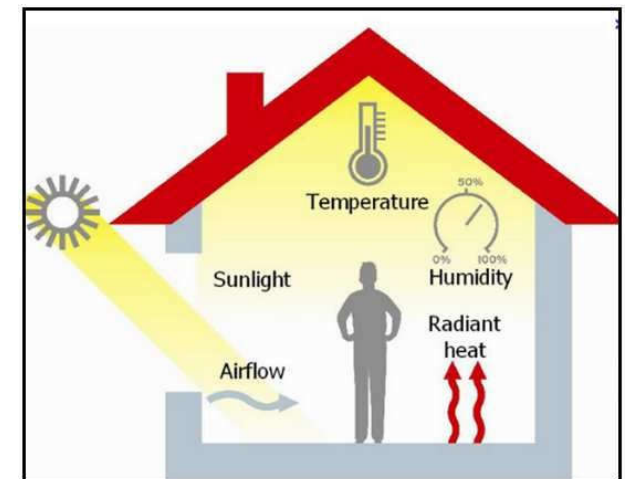


HEAT LOSS FROM A HOUSE

Basic concepts



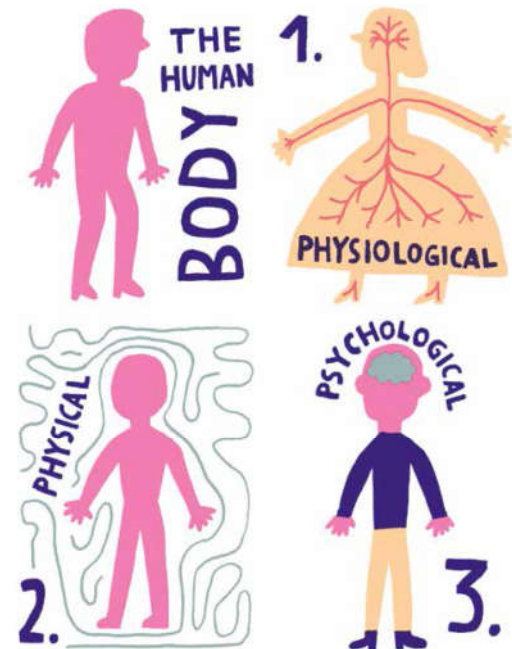
- Aspects that can affect the heat transfer:
 - Air temperature
 - Radiant temperature (long wave infrared radiation (surface temperatures) & short wave infrared radiation (solar radiation))
 - Air velocity
 - Humidity
 - The presence of surface water
 - The temperature of contacting objects



Basic concepts



- The experience people have of the thermal environment that surrounds them will be affected by personal factors such as:
 - Clothing
 - Metabolic heat
 - Wellbeing & sickness
- Personal experience of thermal comfort
 - Thermal satisfaction is experienced via a number of conscious & unconscious interactions among physiological, physical & psychological factors



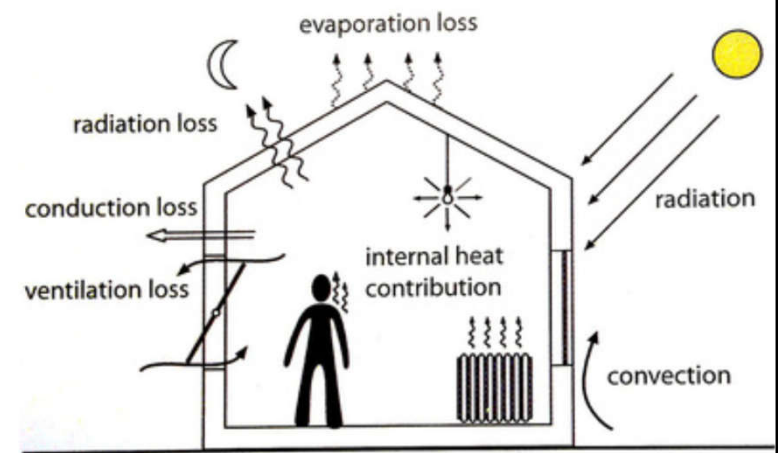
Thermal behaviour of buildings



- Thermal behaviour of buildings

- Heat inputs and outputs:

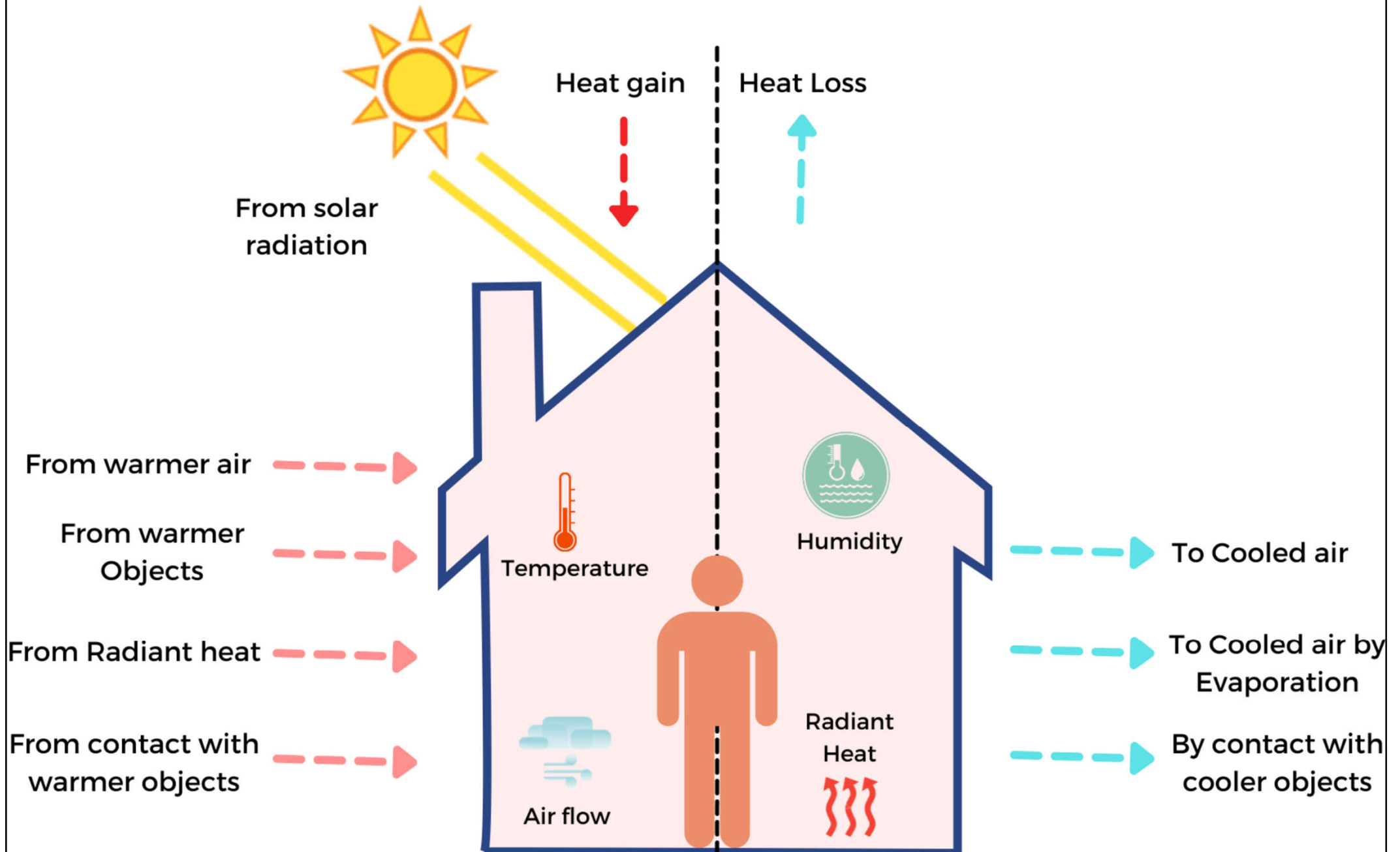
- Q_i – internal heat gain
 - Q_c – conduction heat gain or loss
 - Q_s – solar heat gain
 - Q_v – ventilation heat gain or loss
 - Q_e – evaporative heat loss



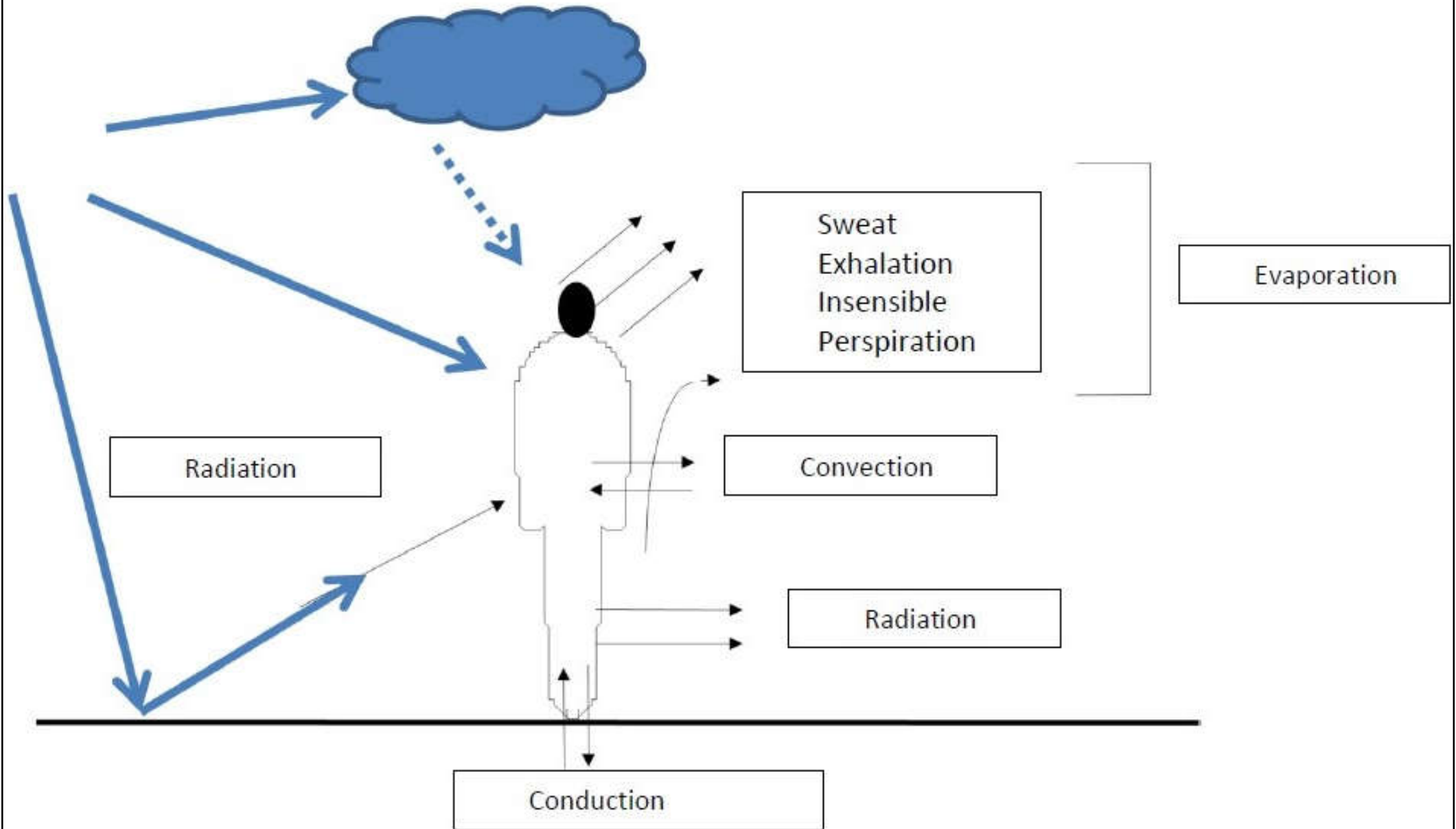
- Thermal balance: $Q_i + Q_c + Q_s + Q_v + Q_e = \Delta S$

- If the sum $\Delta S > 0$, temp. inside the building is increasing, or if it is less than zero, the building is cooling down

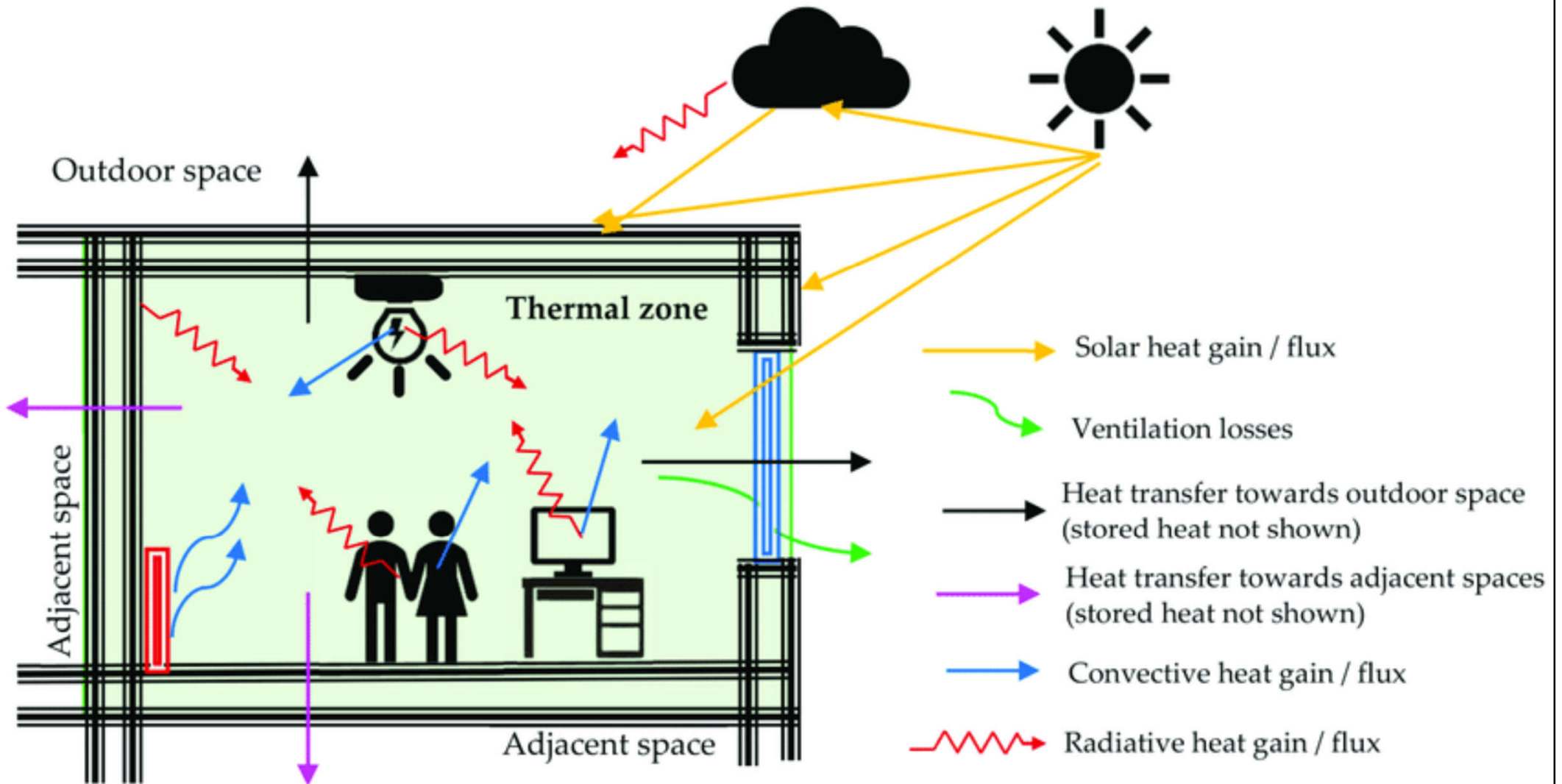
Heat transmission in buildings



Heat transfer at human body



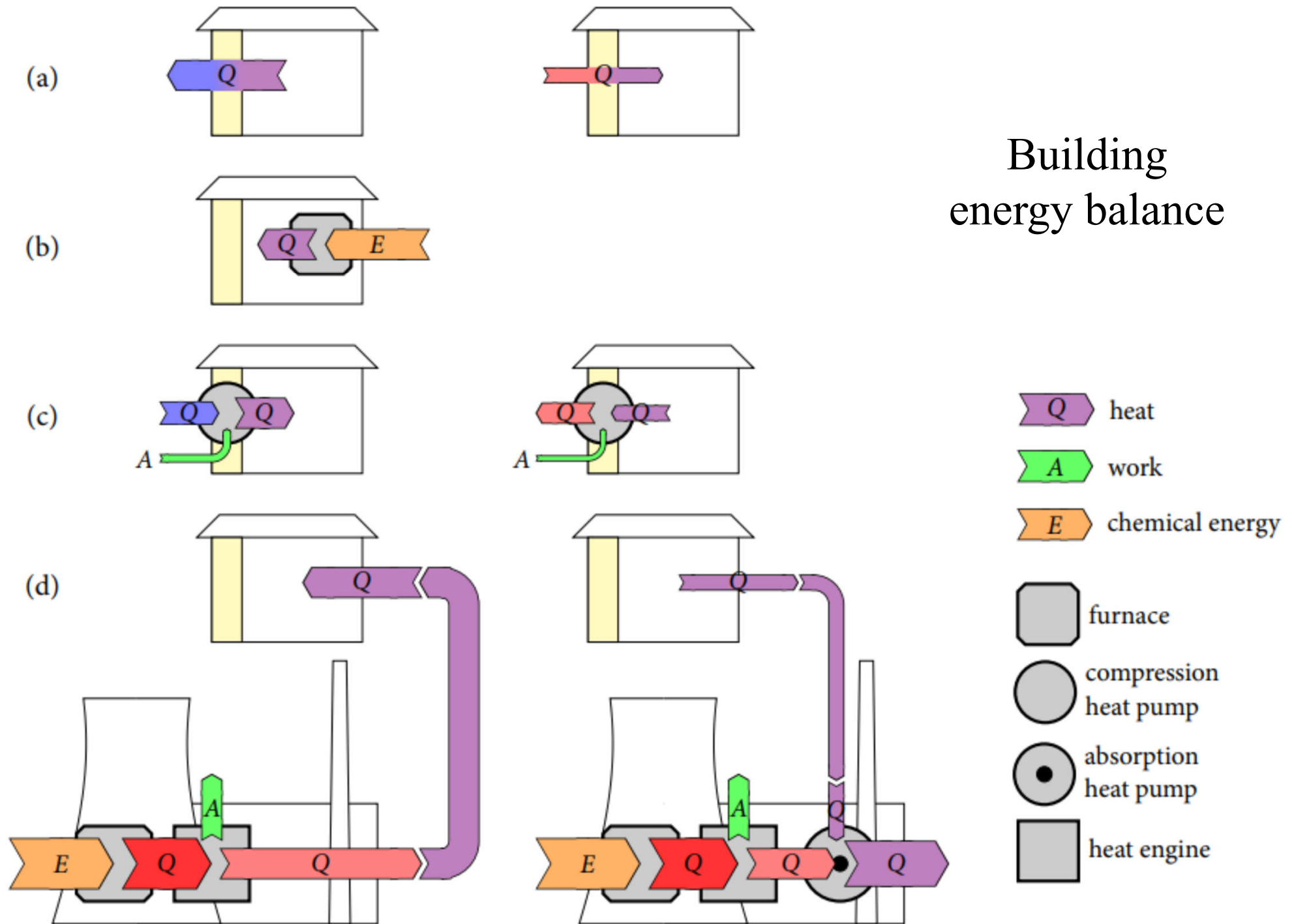
Main energy/heat fluxes affecting the building energy balance



winter (cold) period

summer (warm) period

Building energy balance



Thermal behaviour of buildings



- Steady state heat flow
 - Air temperature: ventilation & building envelope
 - Solar radiation: opaque elements & windows
- Dynamic response of buildings
 - Magnitude of heat flow & its timing
 - Affected by thermal capacity (e.g. massive construction)
 - Periodic heat flow & time lag
 - Thermal response simulation (software programs)

Summary of steady state heat flow expressions

Air temperature

Solar radiation

Ventilation

All elements

Opaque elements

Windows

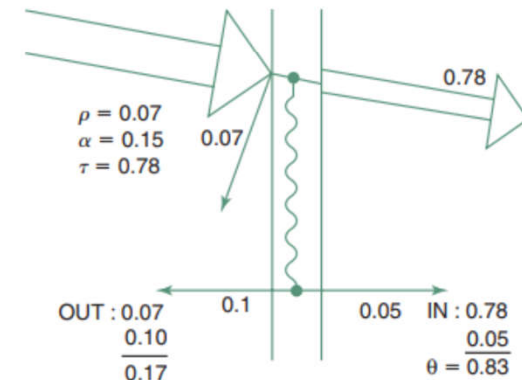
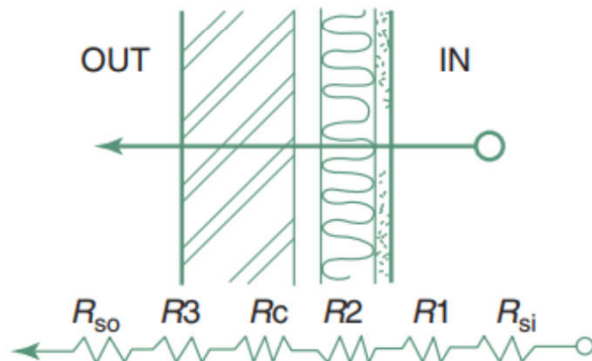
$$\begin{aligned}
 Q_v &= q_v \times \Delta T \\
 q_v &= 1200 \times v_r \\
 &= 0.33 \times V \times N \\
 \Delta T &= T_o - T_i
 \end{aligned}$$

$$\begin{aligned}
 Q_c &= q_c \times \Delta T \\
 q_c &= \Sigma(A \times U) \\
 \Delta T &= T_o - T_i
 \end{aligned}$$

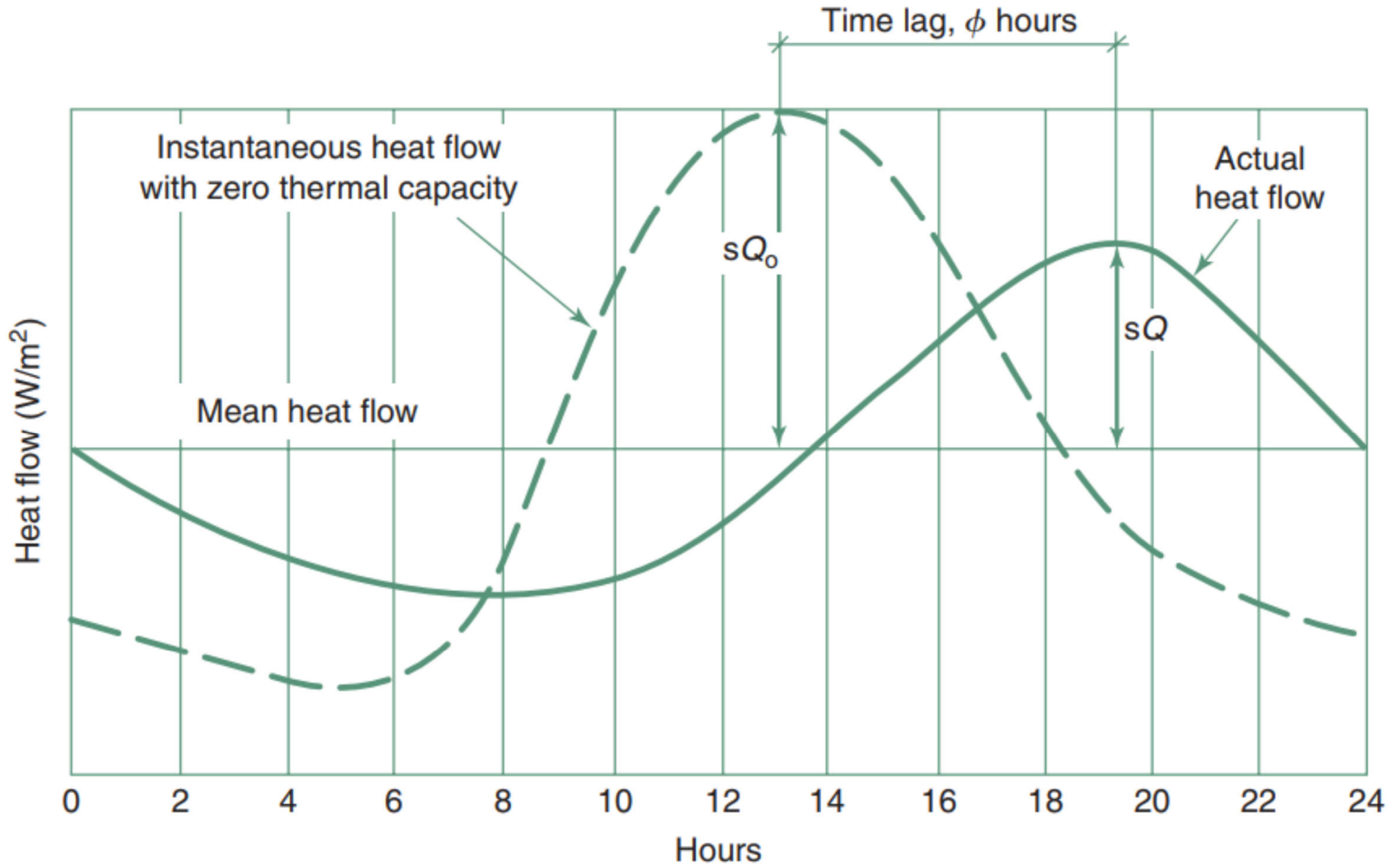
$$\begin{aligned}
 Q_{s_o} &= q_c \times dTe \\
 q_c &= \Sigma(A \times U) \\
 dTe &= G \times \alpha \times R_{so} \\
 \text{roof: } &(G \times \alpha - E) \times R_{so}
 \end{aligned}$$

$$Q_{s_w} = A \times G \times \theta$$

$$Q = (q_c + q_v) \times \Delta T + Q_{s_o} + Q_{s_w}$$



Heat flow through a real wall, compared with a wall of zero mass

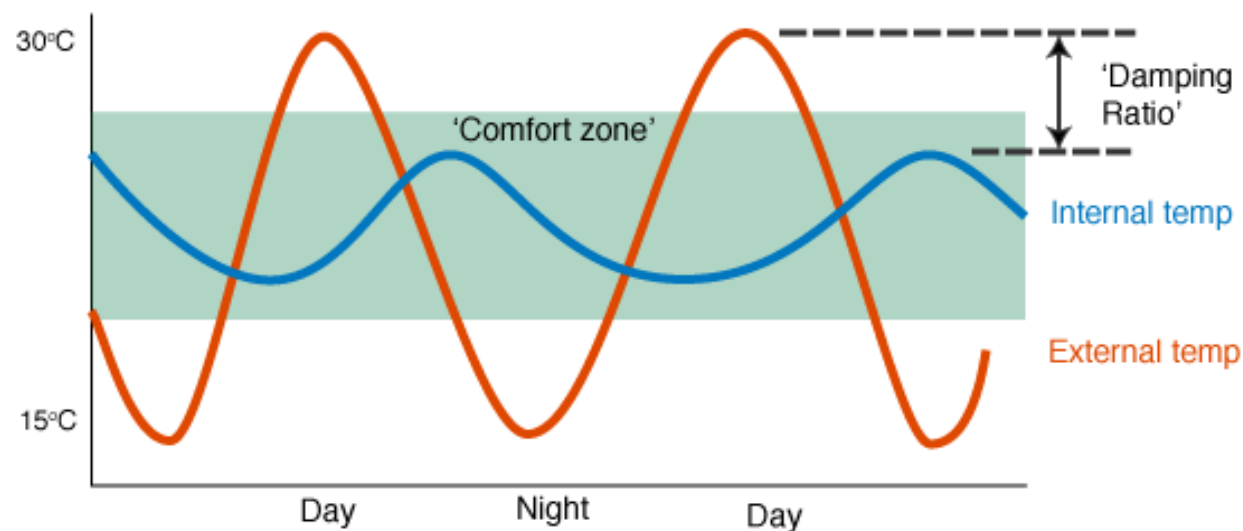


Thermal behaviour of buildings



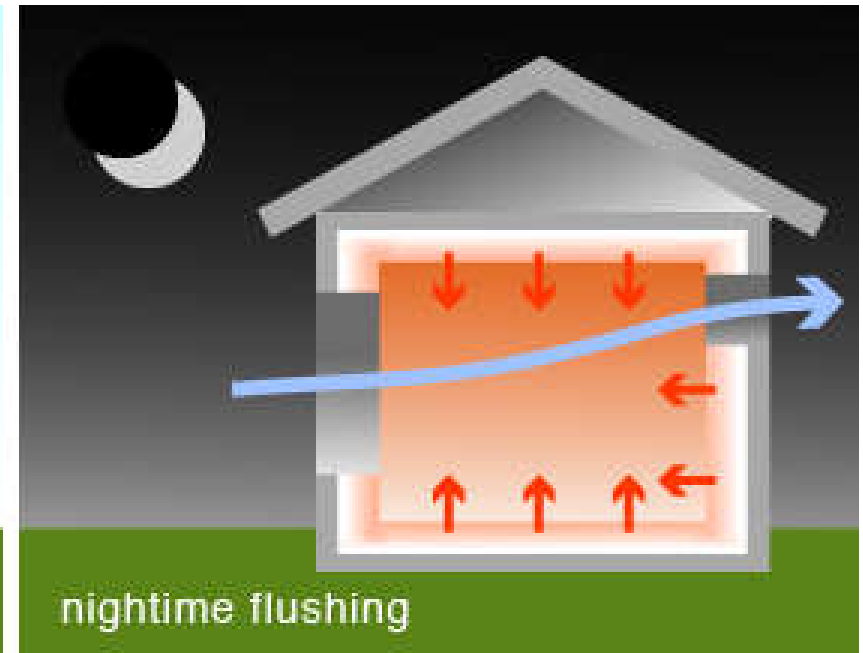
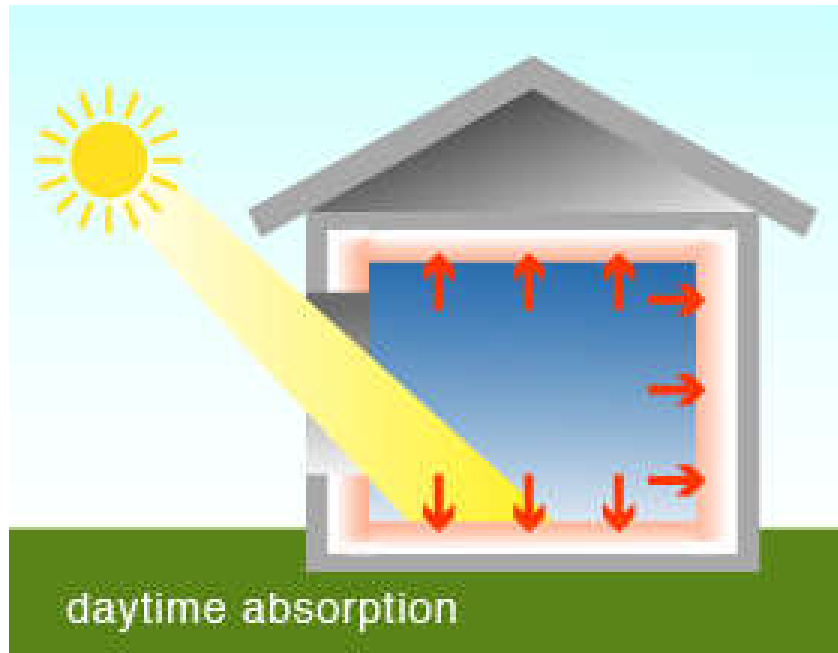
- Thermal mass

- A material's capacity to absorb, store and release heat, measured by thermal admittance [$\text{W}/(\text{m}^2 \cdot \text{K})$]
 - Specific heat capacity, density, thermal conductivity
- To assess heat flows into & out of thermal storage

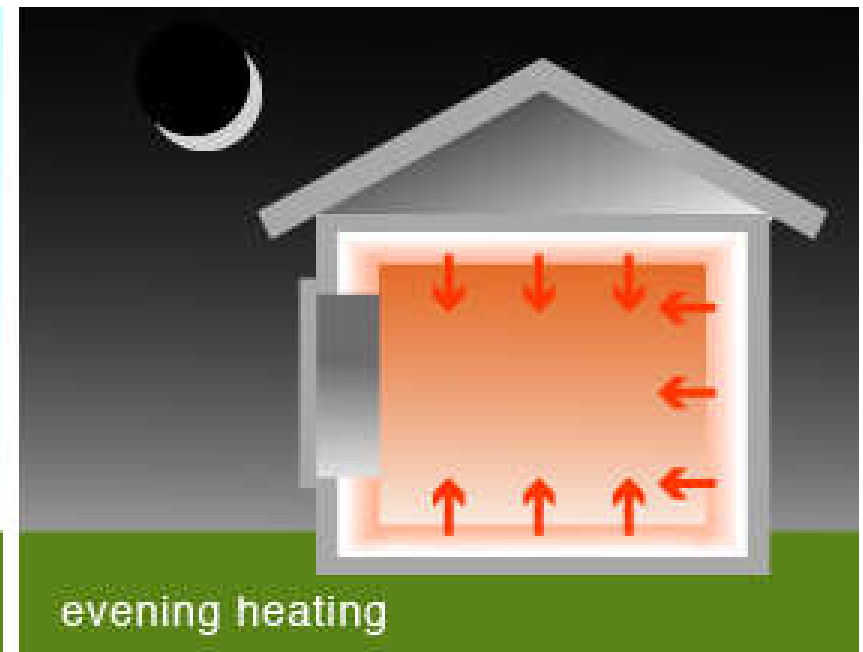
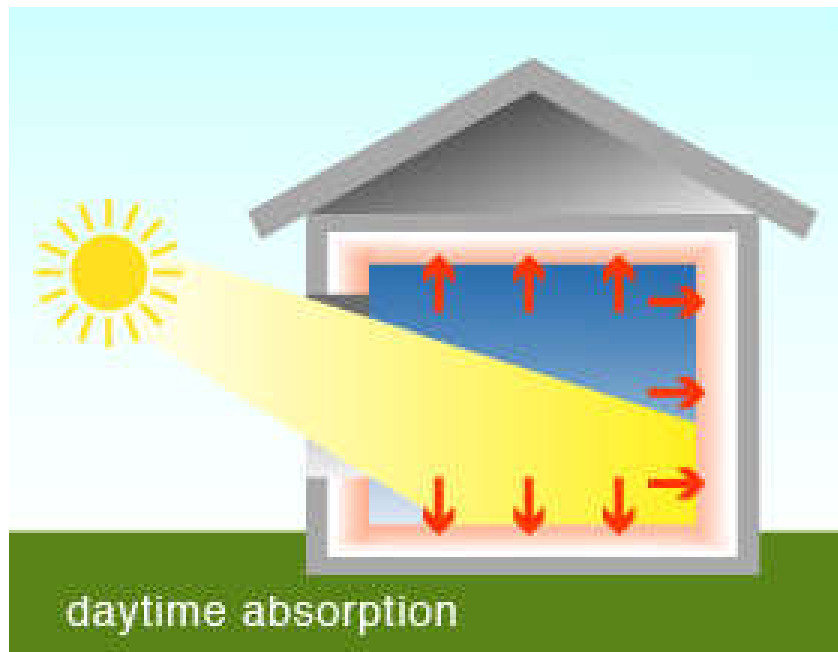


How thermal mass works

Summer cooling



Winter heating

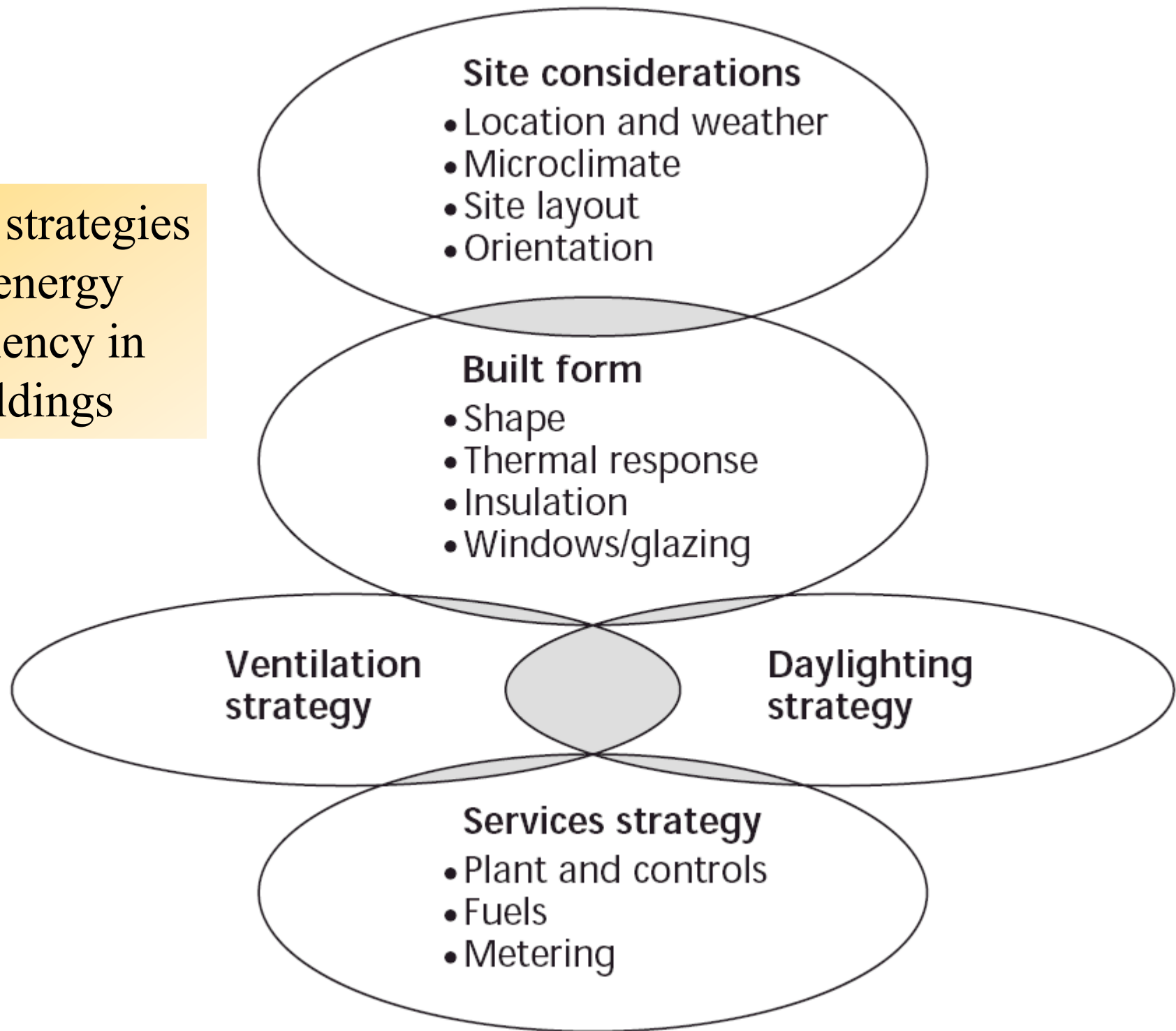


Thermal behaviour of buildings



- Within the built environment, the thermal environment can be influenced by:
 - 1. Passive building design (e.g. shading, windows, insulation, thermal mass, natural ventilation and so on)
 - 2. Active building systems (e.g. heating, cooling and air conditioning)
 - 3. Personal behaviour (e.g. removing clothing, reducing activity and so on)

**Design strategies
for energy
efficiency in
buildings**

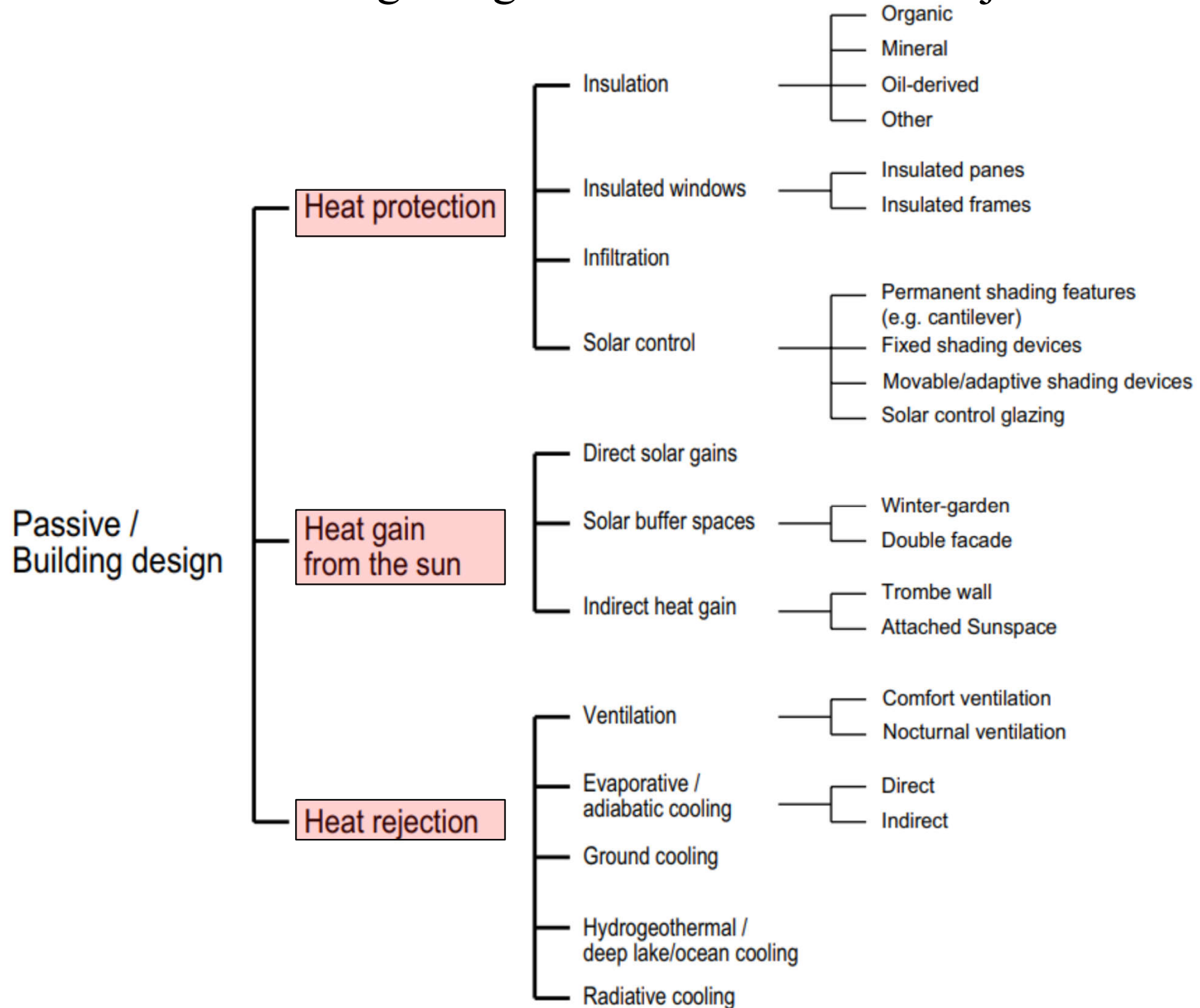




Passive building design

- *Passive design* uses layout, fabric and form to reduce or remove mechanical cooling, heating, ventilation & lighting demand
 - Passive cooling/heating + natural ventilation
 - Examples: optimising spatial planning & orientation to control solar gains & maximise daylighting, manipulating the building form & fabric to facilitate natural ventilation strategies and making effective use of thermal mass to help reduce peak internal temperatures

Passive building design measures and their objective



Passive heat dissipation strategies according to the heat sinks

AIR AS HEAT SINK

Comfort ventilation

Nocturnal ventilation

Evaporative cooling

SKY AS HEAT SINK

Radiative cooling

EARTH AS HEAT SINK

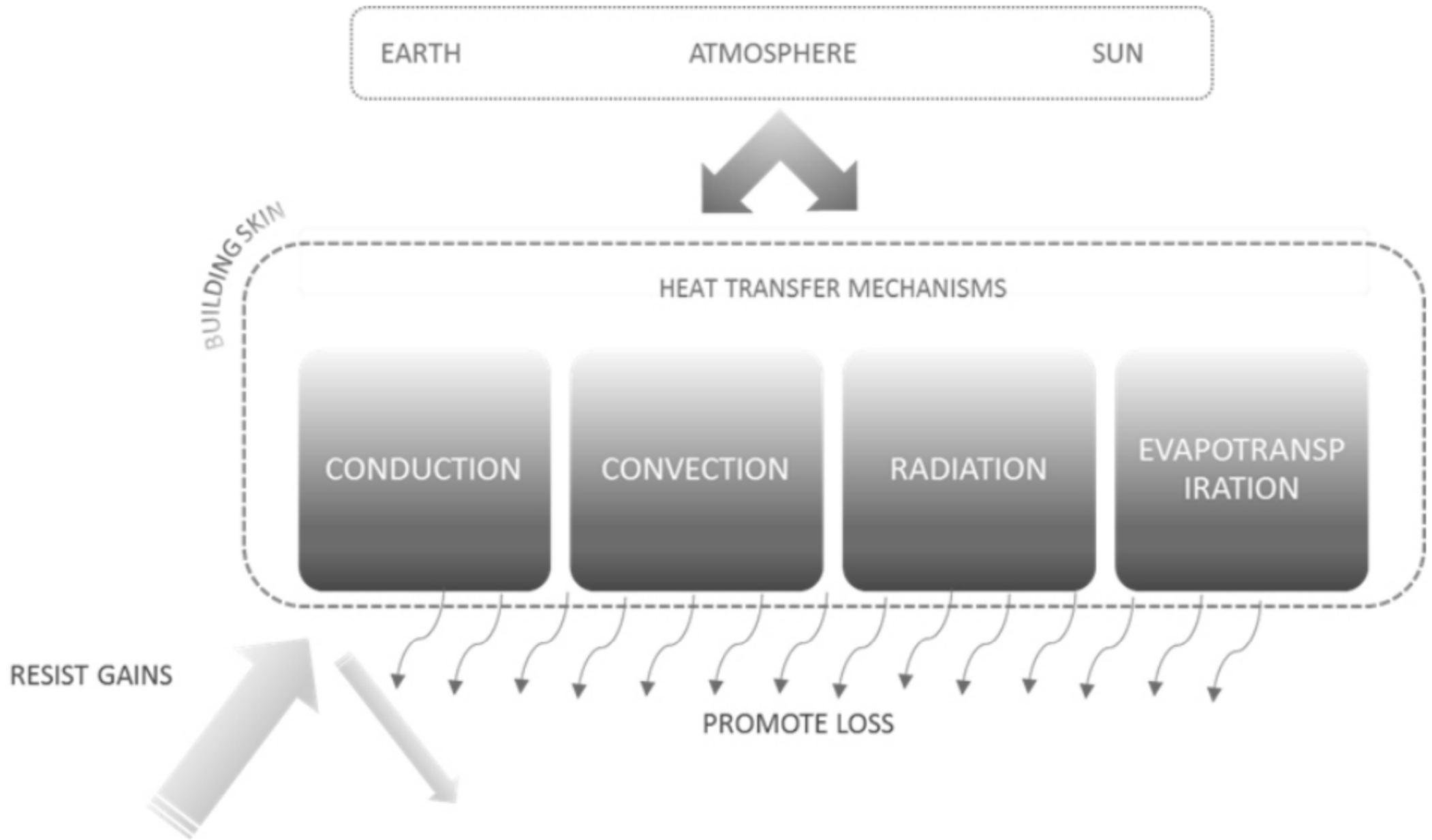
Geothermal cooling

WATER AS HEAT SINK

Hydrogeothermal

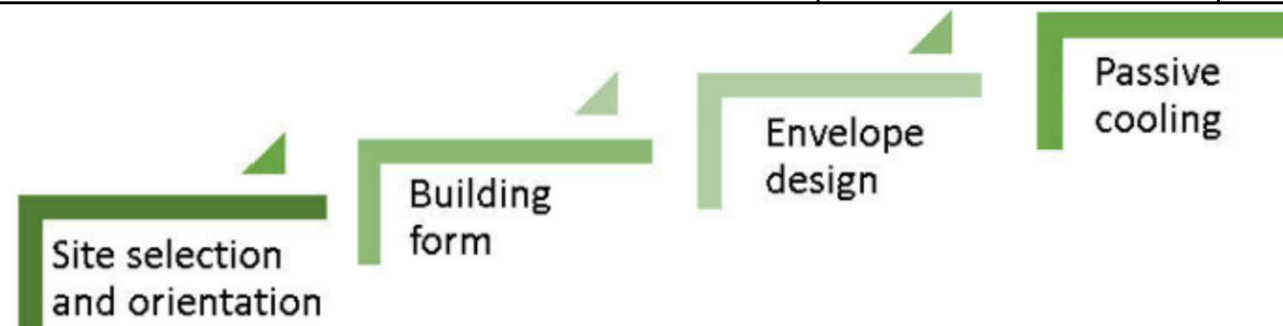
Deep ocean/lake

Bioclimatic design strategies for buildings in hot climate: to minimise heat gains into the building and promote heat loss



Passive/Bioclimatic building design strategies for hot climates

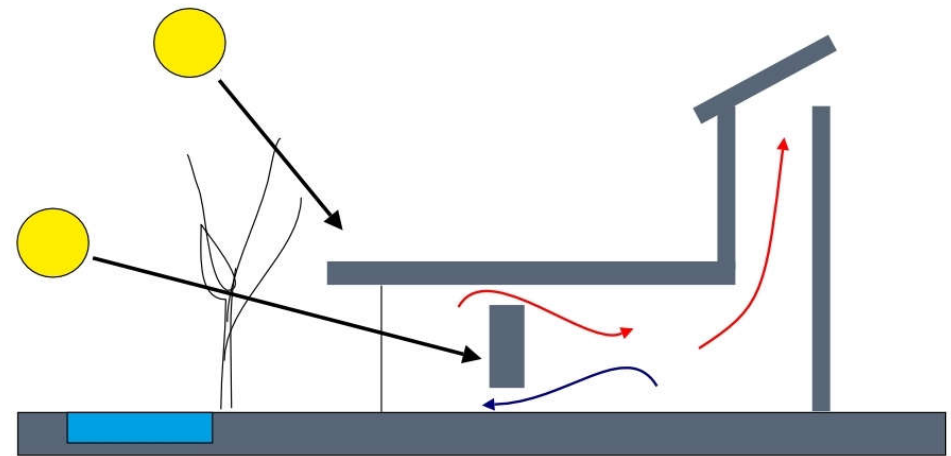
Strategy	Hot & dry	Hot & humid
Compact geometry	√	X
Exterior shading	√	√
Daylighting	√	√
Window low solar heat gain coefficient	√	√
Cross/stack ventilation (if naturally ventilated)	√	√
Building permeability (if naturally ventilated)	X	√
Roof insulation	√	√
Wall insulation (exterior)	√	X
High thermal mass	√	X
Low thermal mass	X	√
Evaporative cooling	√	X





Passive building design

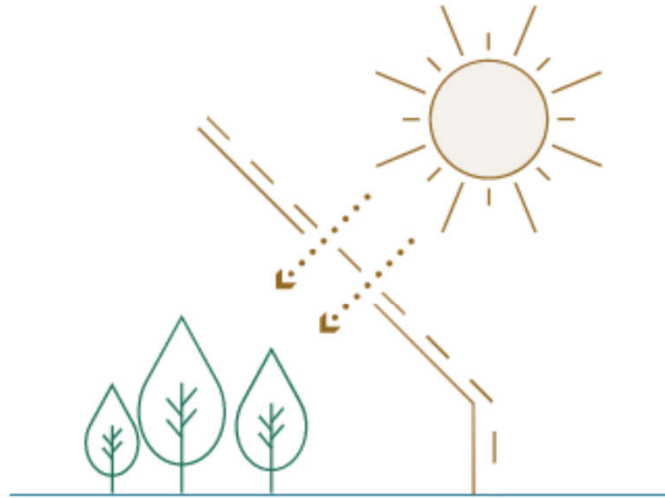
- Passive design considerations:
 - Location, landscape, orientation
 - Massing, shading
 - Material selection
 - Thermal mass, insulation
 - Internal layout
 - The positioning of openings to allow the penetration of solar radiation, visible light and for ventilation



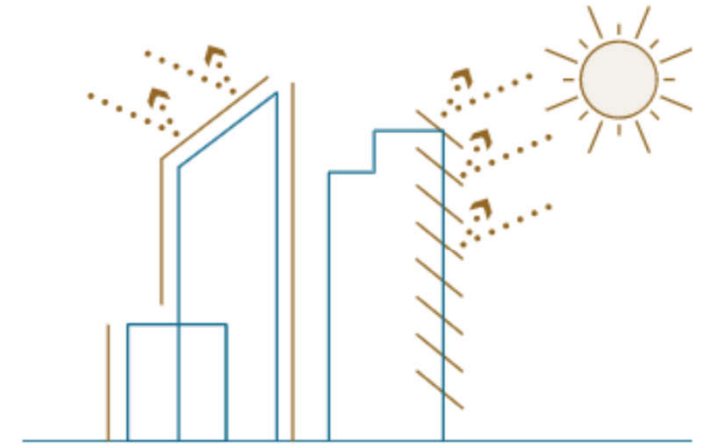
Different aspects of passive design approaches



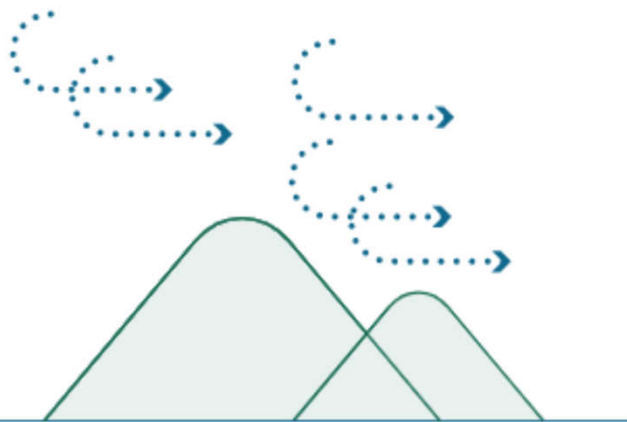
Mitigating heat island effect or elevated temperature



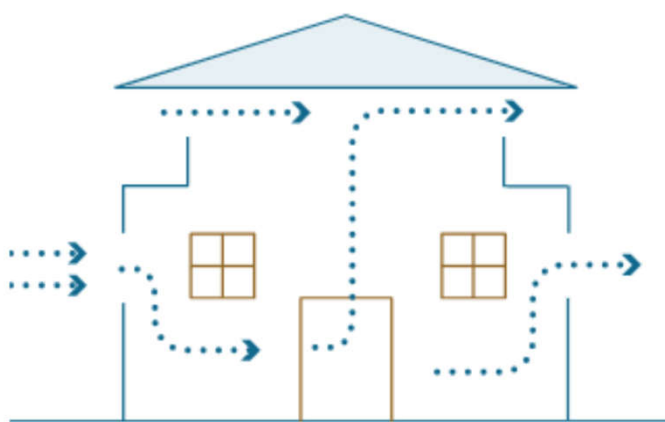
Daylighting



Reducing heat gain through building envelopes



Natural ventilation



Passive cooling



Air ventilation around buildings



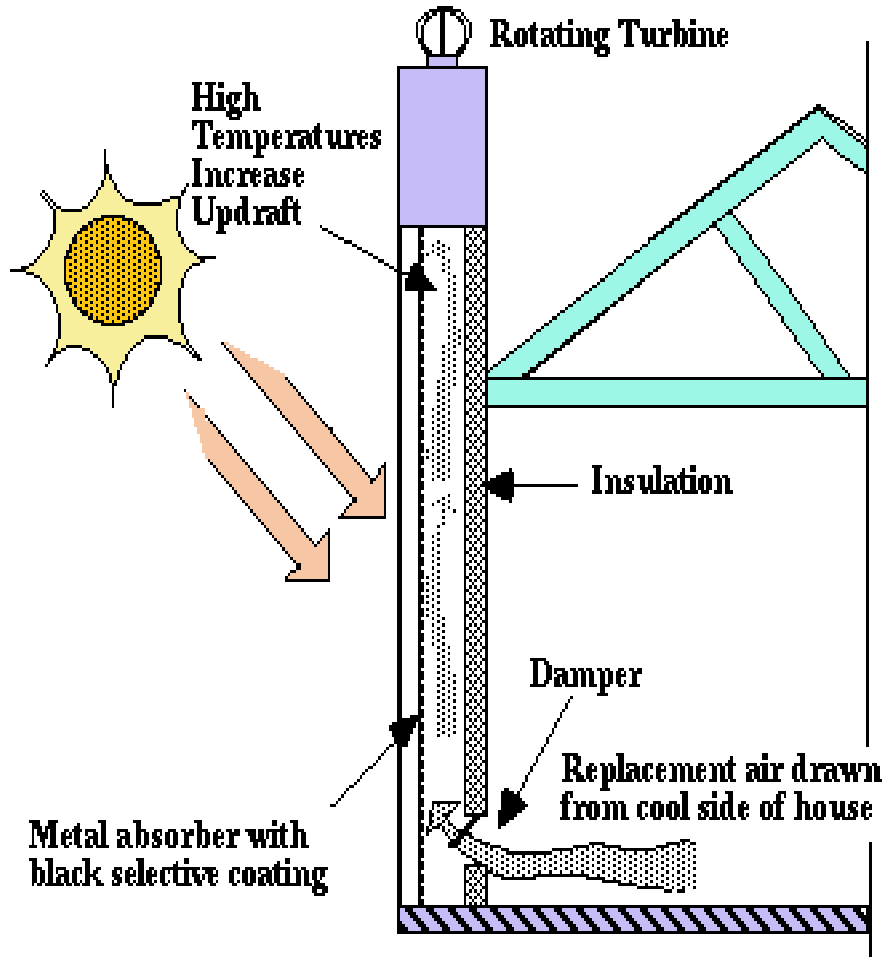
Passive building design

- Passive cooling

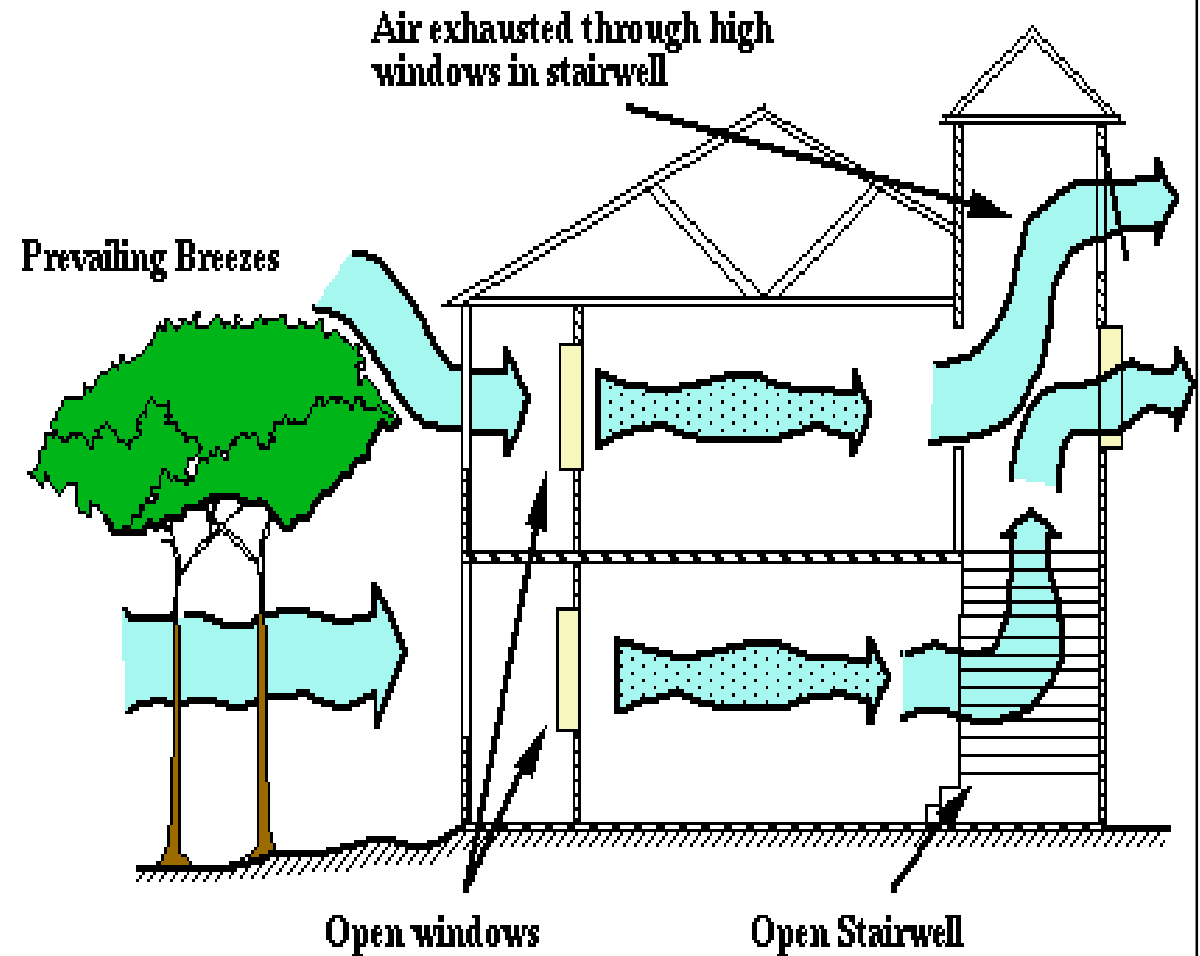


- A building design approach that focuses on *heat gain control* and *heat dissipation* in a building in order to improve the indoor thermal comfort with *low or nil energy consumption*
- This approach works either by preventing heat from entering the interior (*heat gain prevention*) or by removing heat from the building (*natural cooling*)

Examples of passive cooling designs



Thermal chimney



Natural ventilation

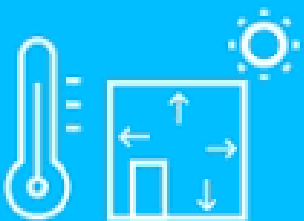


Passive building design

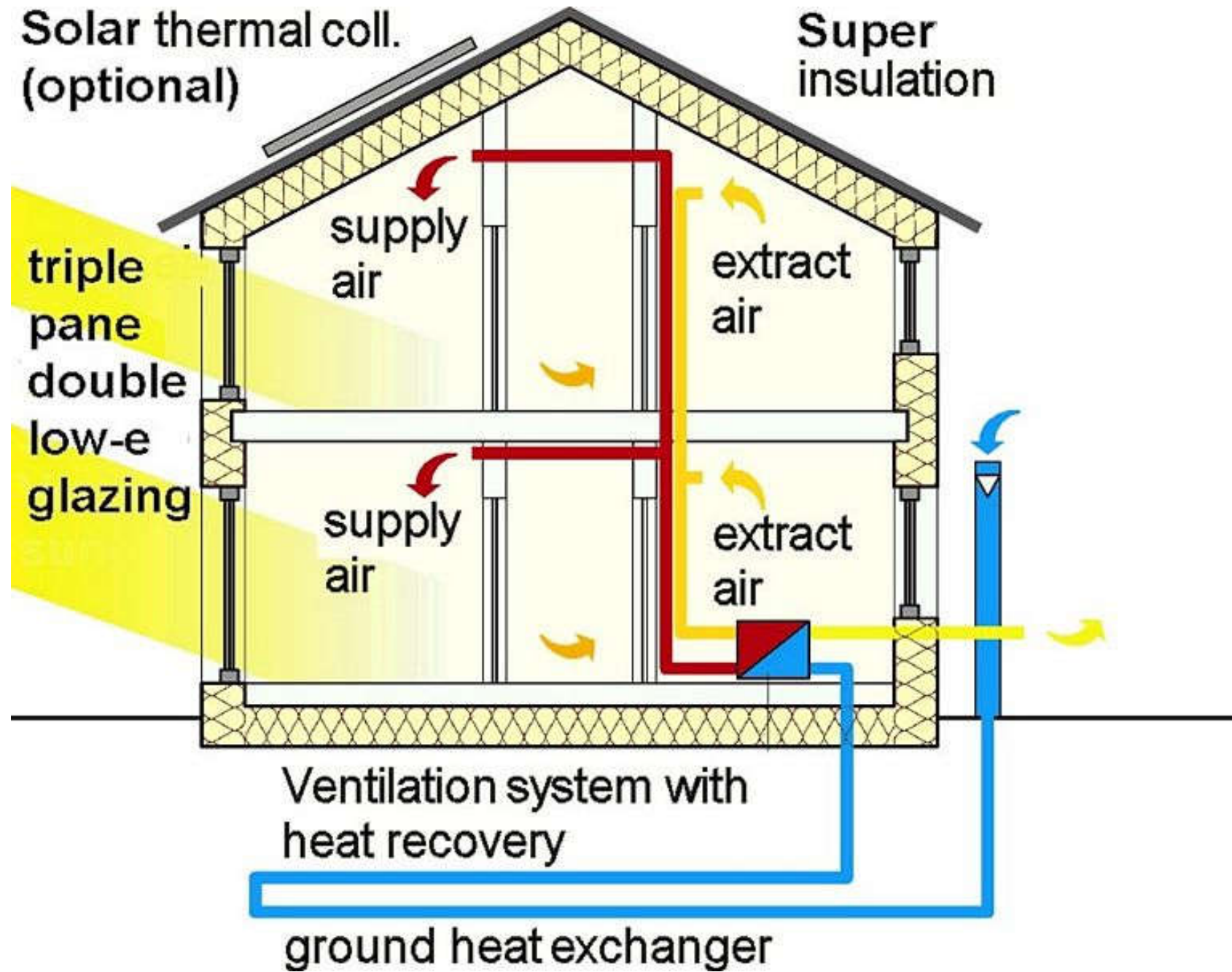
- **Passive cooling (cont'd)**

- Natural cooling utilizes on-site energy, available from the natural environment, combined with the architectural design of building components (e.g. building envelope), rather than mechanical systems to dissipate heat

- It depends not only on the architectural design but how it uses the local site natural resources as heat sinks (i.e. everything that absorbs or dissipates heat). Examples of on-site heat sinks are the upper atmosphere (night sky), the outdoor air (wind), and the earth/soil



Passive house design to achieve low energy requirements for the building energy balance





Passive building design

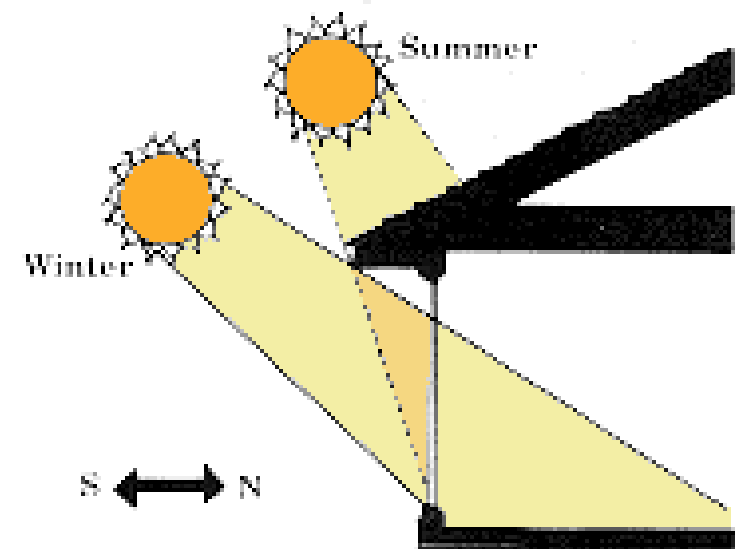
- **Passive cooling (cont'd)**

- Preventative techniques

- Microclimate and site design
- Solar control
- Building form and layout
- Thermal insulation
- Behavioral and occupancy patterns
- Internal gain control

- Modulation and heat dissipation techniques

- Thermal mass + Natural cooling

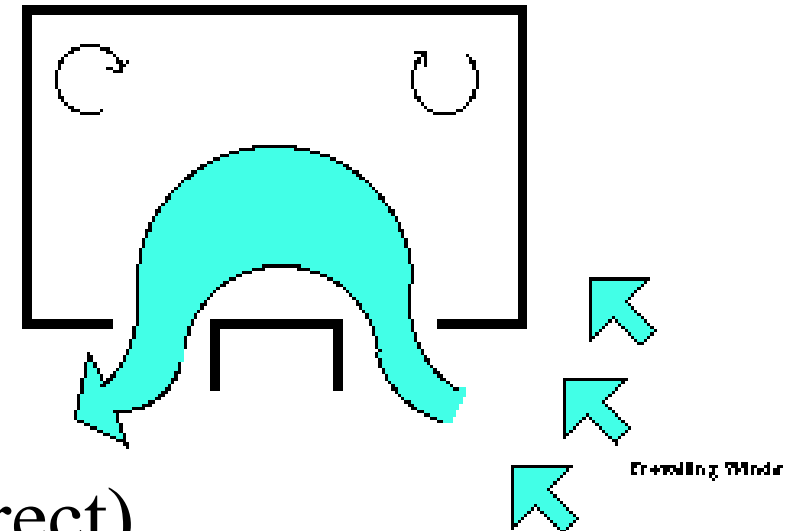




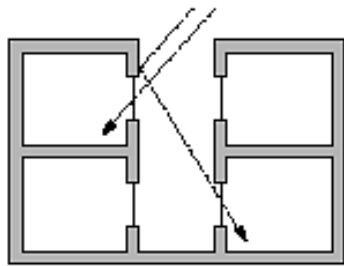
Passive building design

- Passive cooling (cont'd)

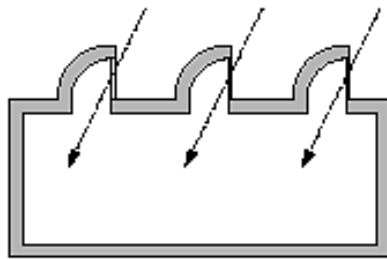
- Ventilation
 - Cross ventilation
 - Stack ventilation
 - Night flush ventilation
- Radiative cooling (direct/indirect)
- Evaporative cooling
- Earth coupling (direct/indirect)



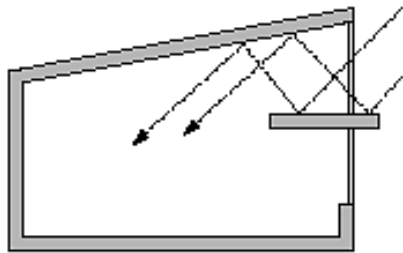
Daylighting design and control



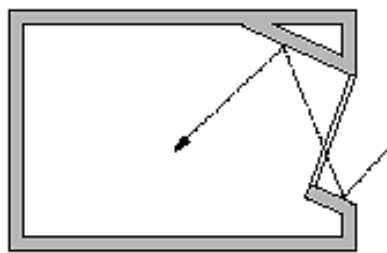
Light well



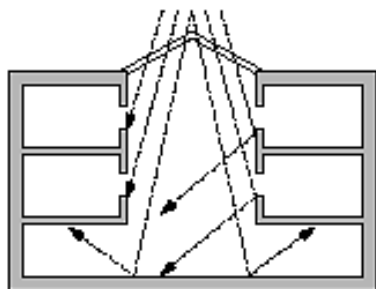
Roof monitor



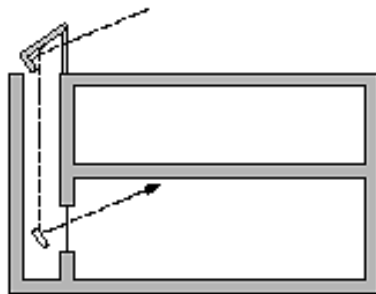
Light shelf



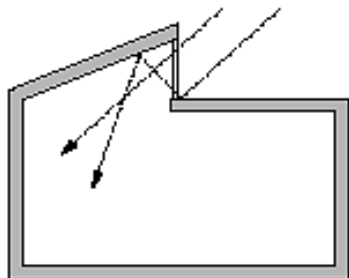
External reflectors



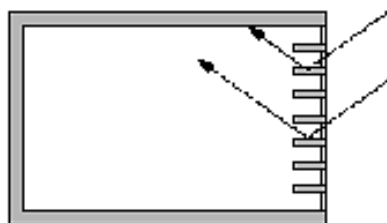
Atrium



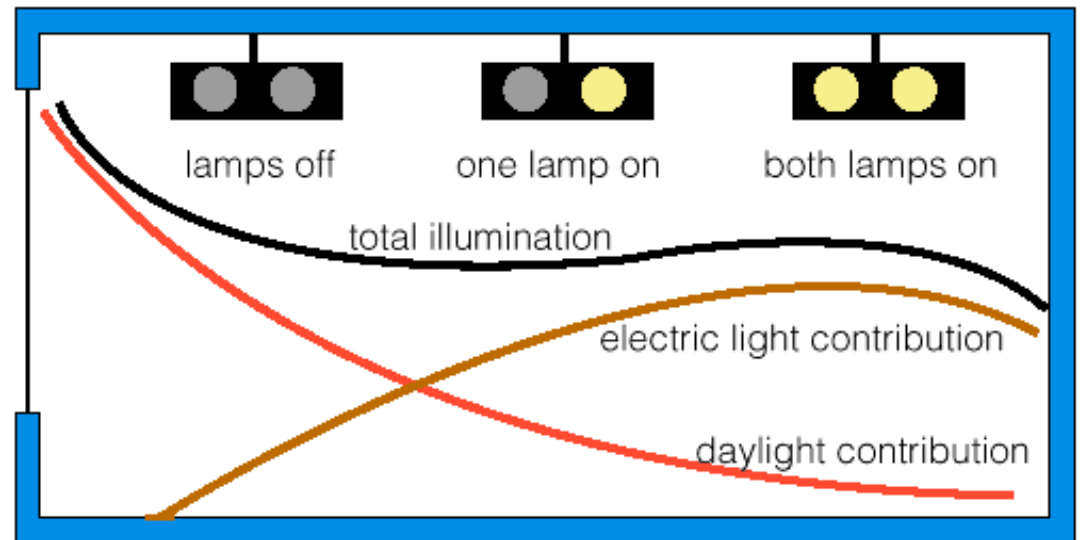
Light duct



Clerestory



Reflective blinds

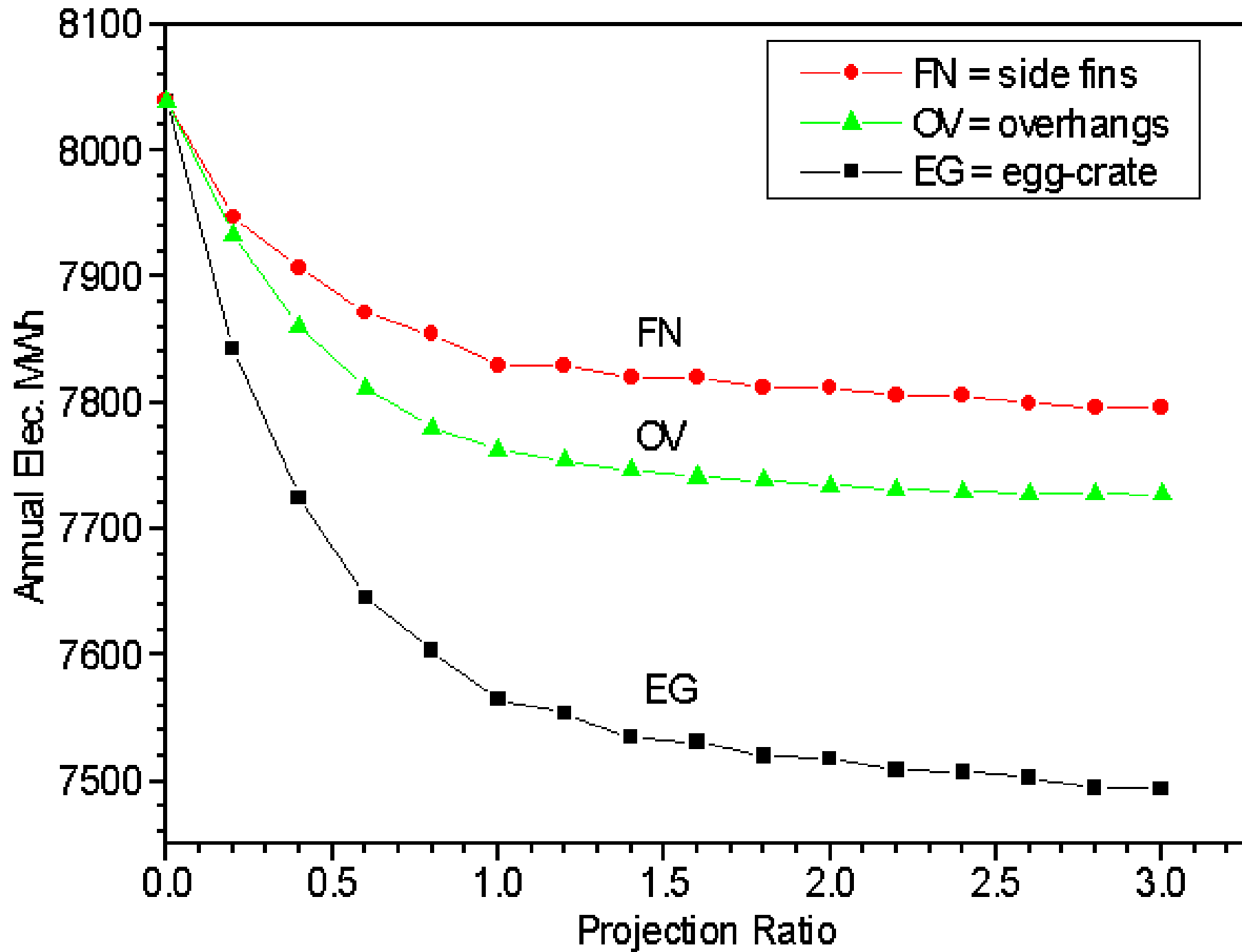




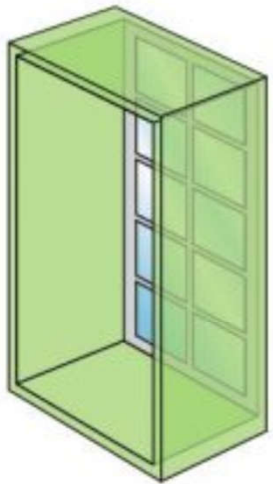
Solar control

- First determine when solar radiation would be a welcome input (solar heating for the underheated period) or when it should be excluded (the overheated period)
- Shading design 遮陽設計
 - 1. Vertical devices (e.g. vertical louvres or fins)
 - 2. Horizontal devices (e.g. projecting eaves)
 - 3. Egg-crate devices

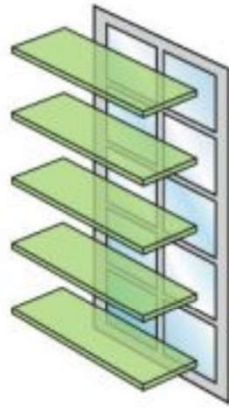
Example: Effects of external shading on energy consumption



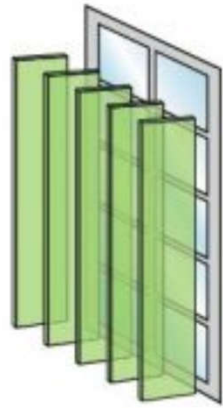
Examples of window shading methods



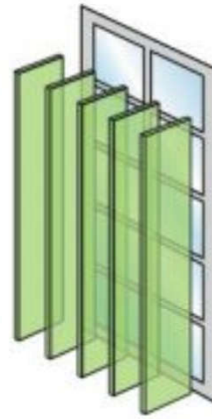
Recessed window



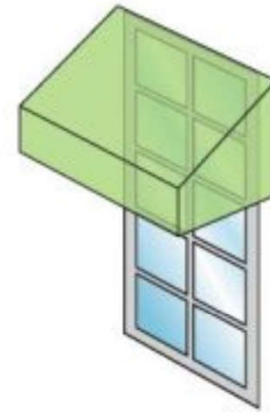
Horizontal fixed shade



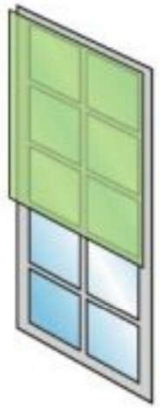
Vertical movable shade



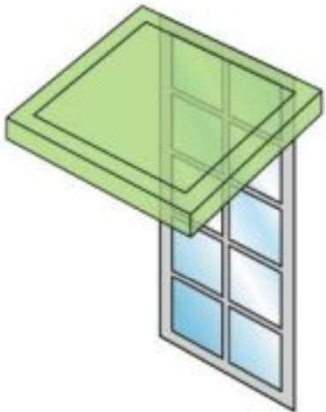
Vertical fixed shade



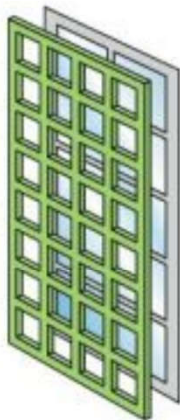
Awning



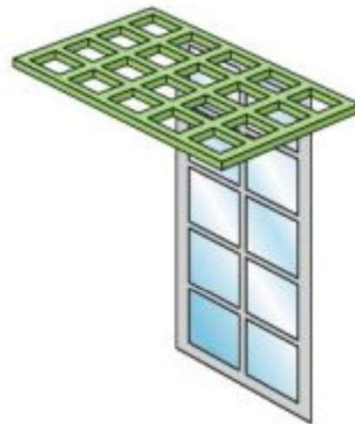
Exterior operable shade



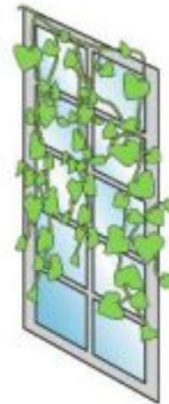
Bahama shutter



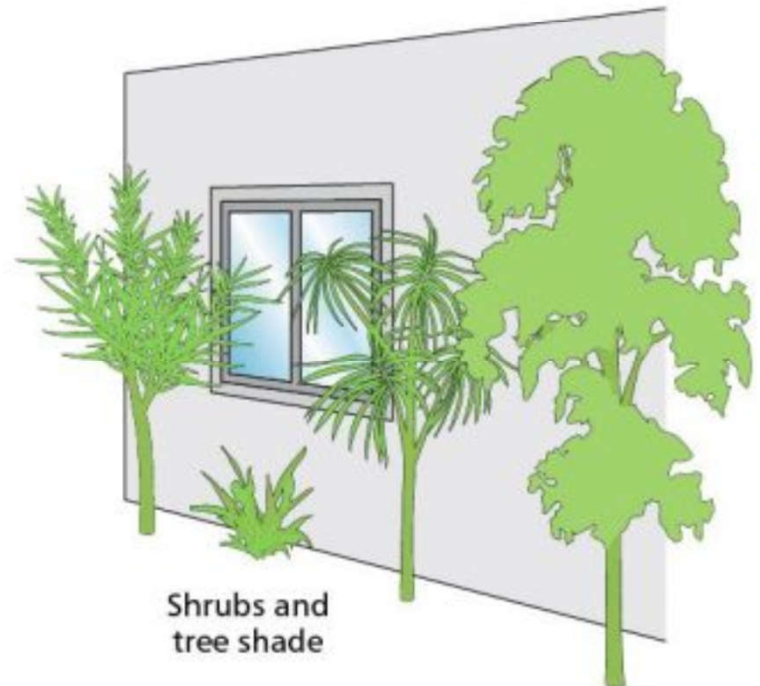
Trellis



Perforated horizontal overhang

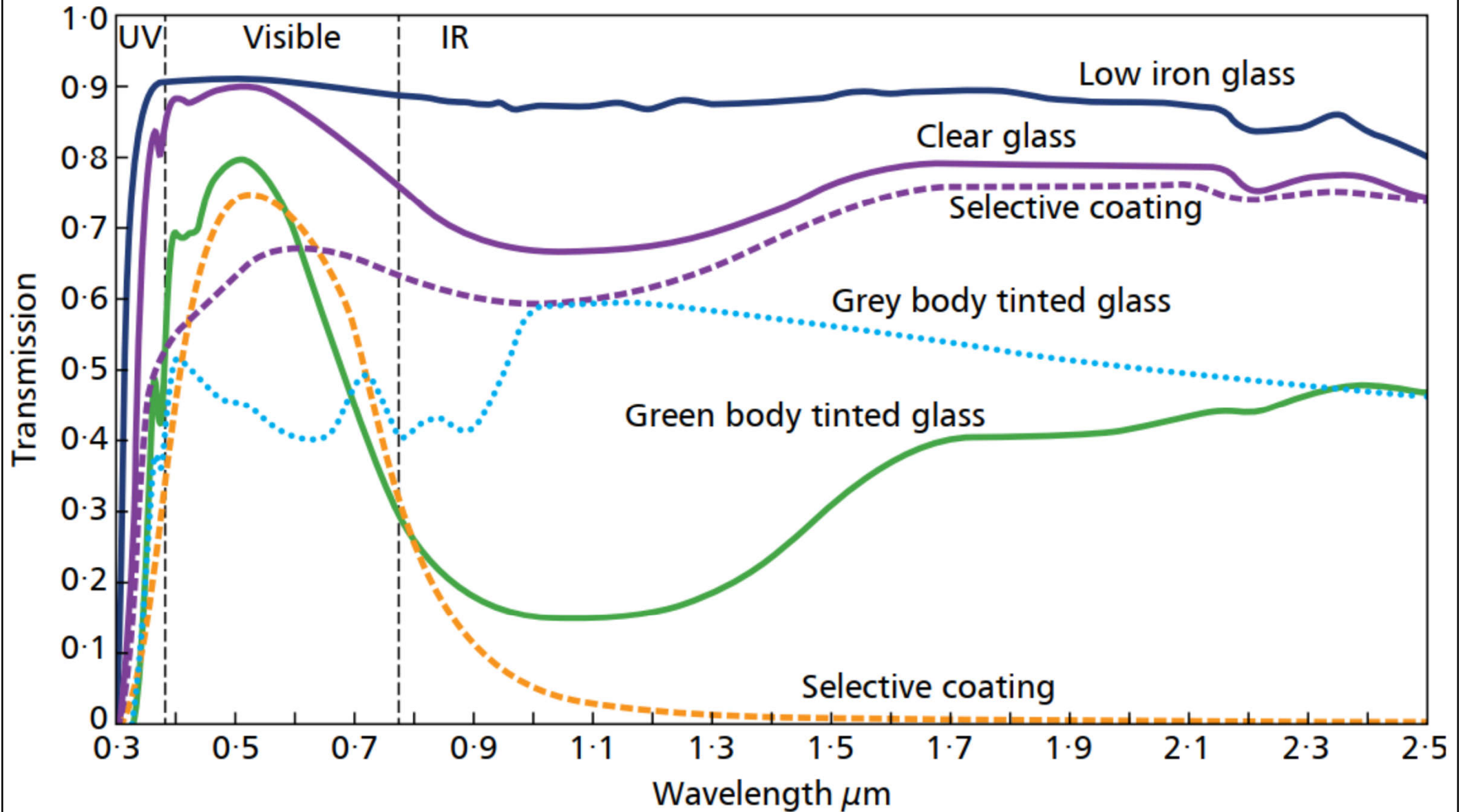


Vegetation on window

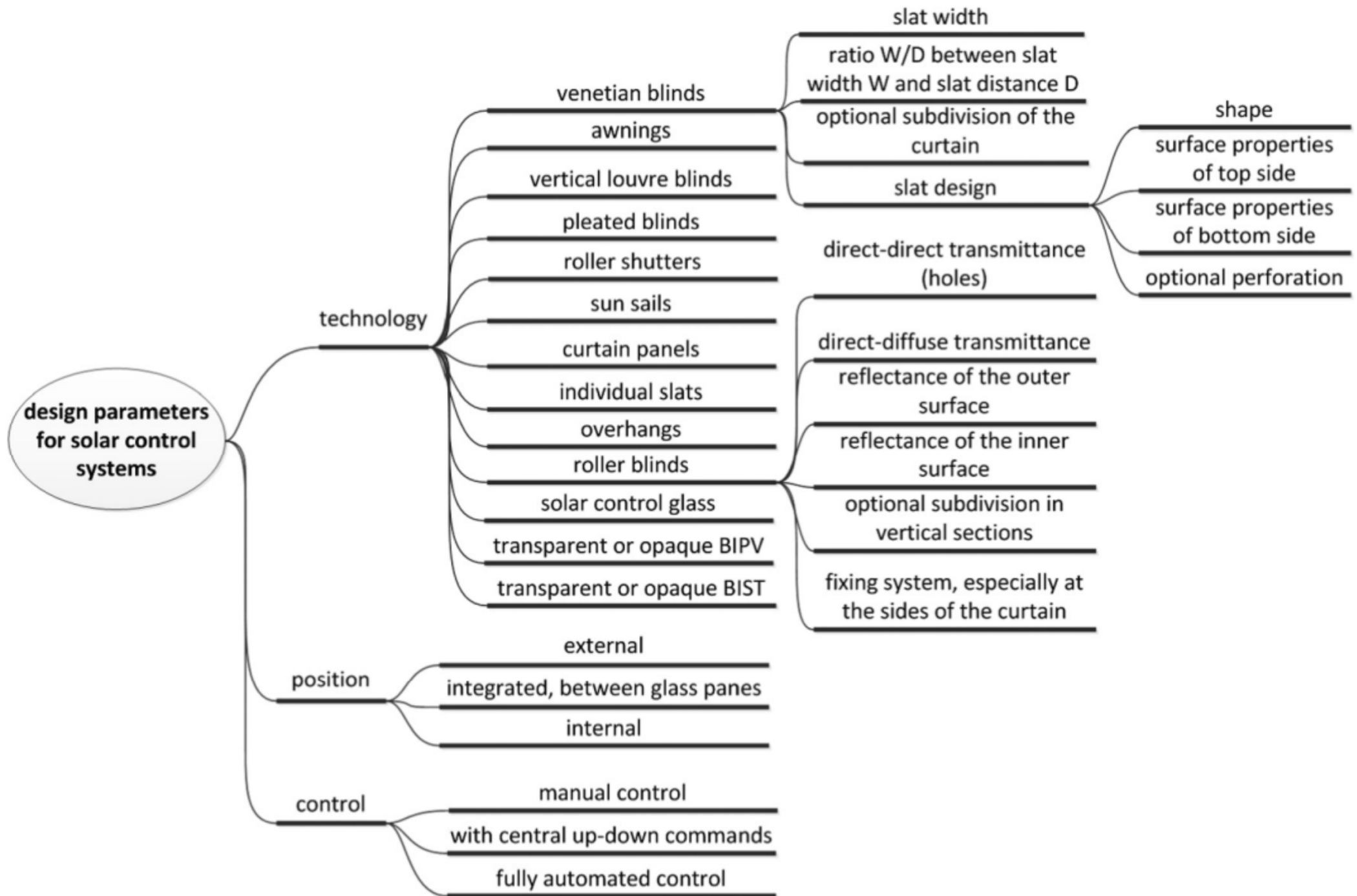


Shrubs and tree shade

Spectral transmittance of different glass types



Design parameters for solar-control systems





Solar control

- Glare/Thermal control strategies:
 - Automated exterior shading
 - Fixed exterior architectural shading
 - Exterior fabric awnings
 - High performance glazing
 - Operable windows
 - Automated interior shading / double skin systems
 - Manual interior shading

Different shading solutions & their effects



Interior shading, Venetian blind



Exterior shading, roller shutter



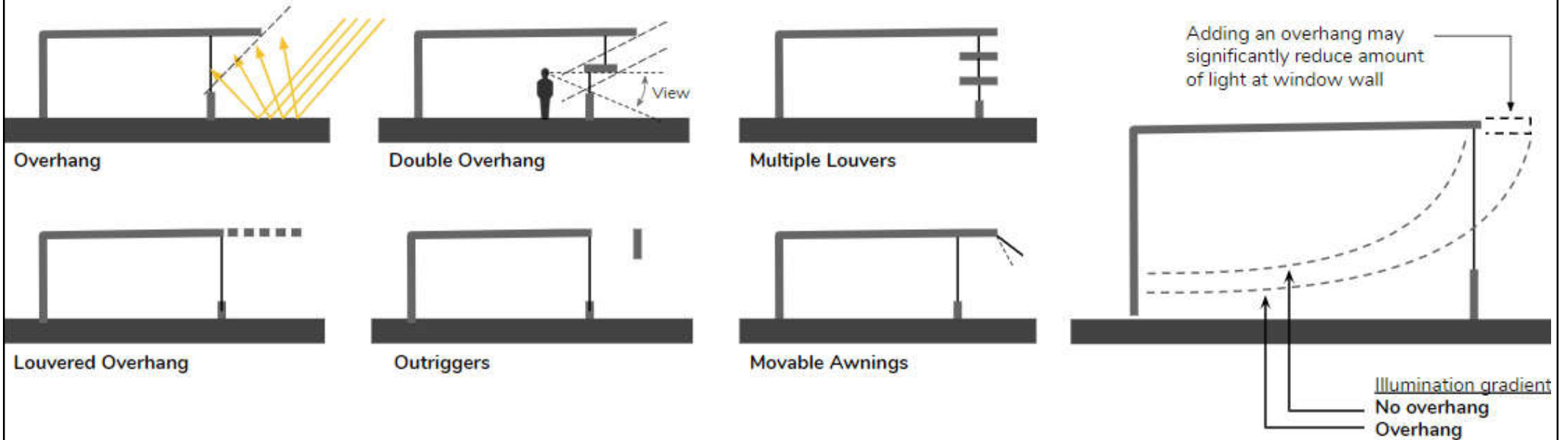
Interior shading, pleated Blind



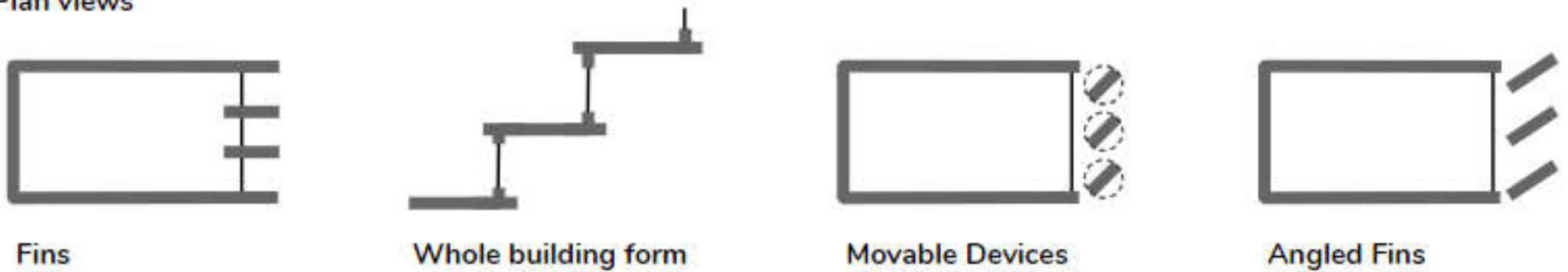
Exterior shading, awning blind

Horizontal & vertical shading devices

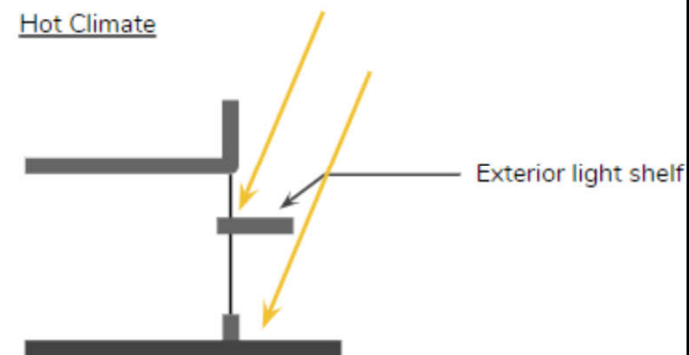
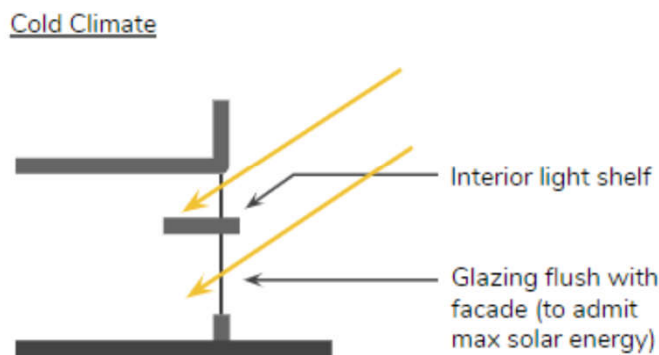
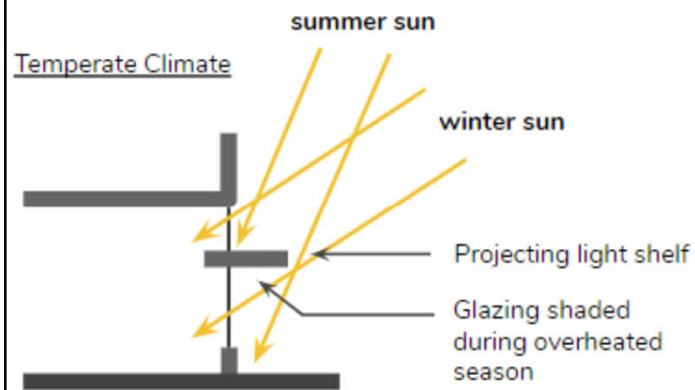
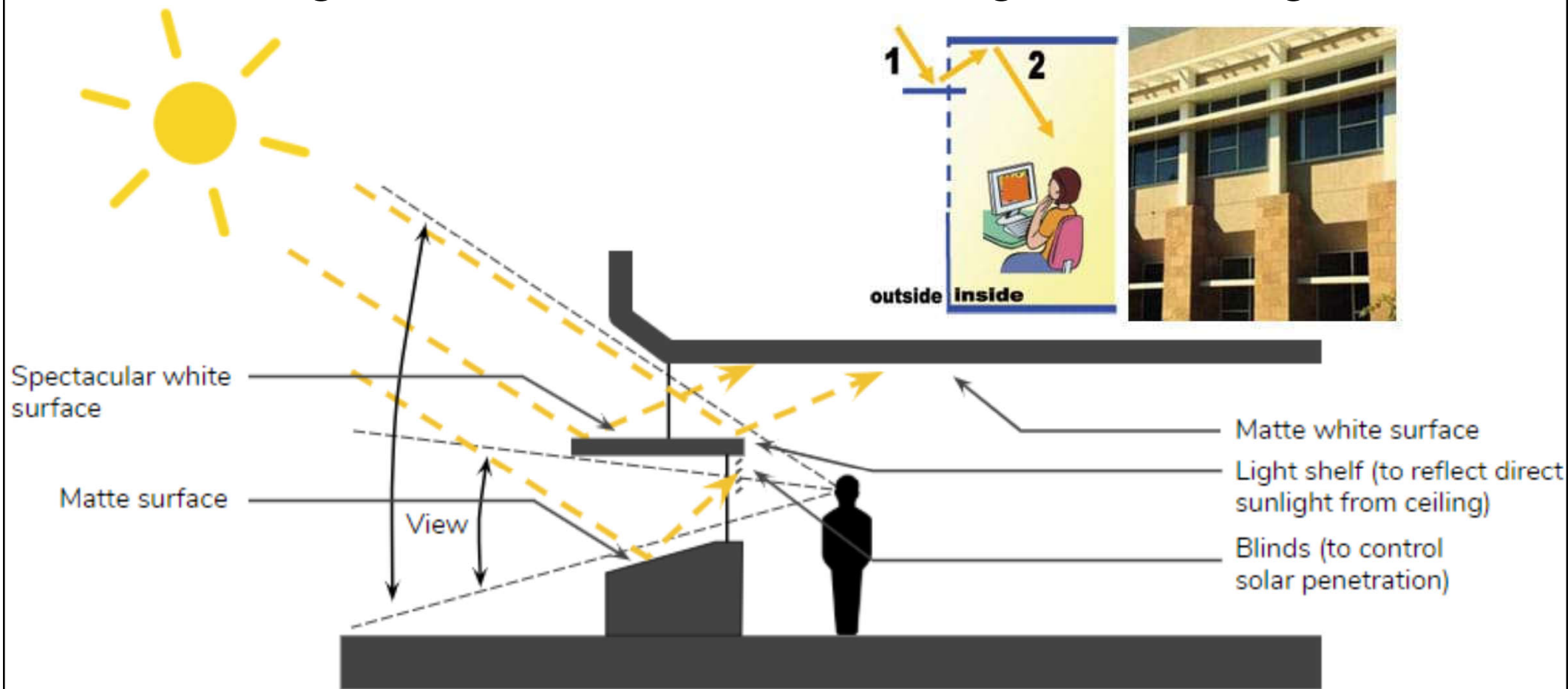
Section views



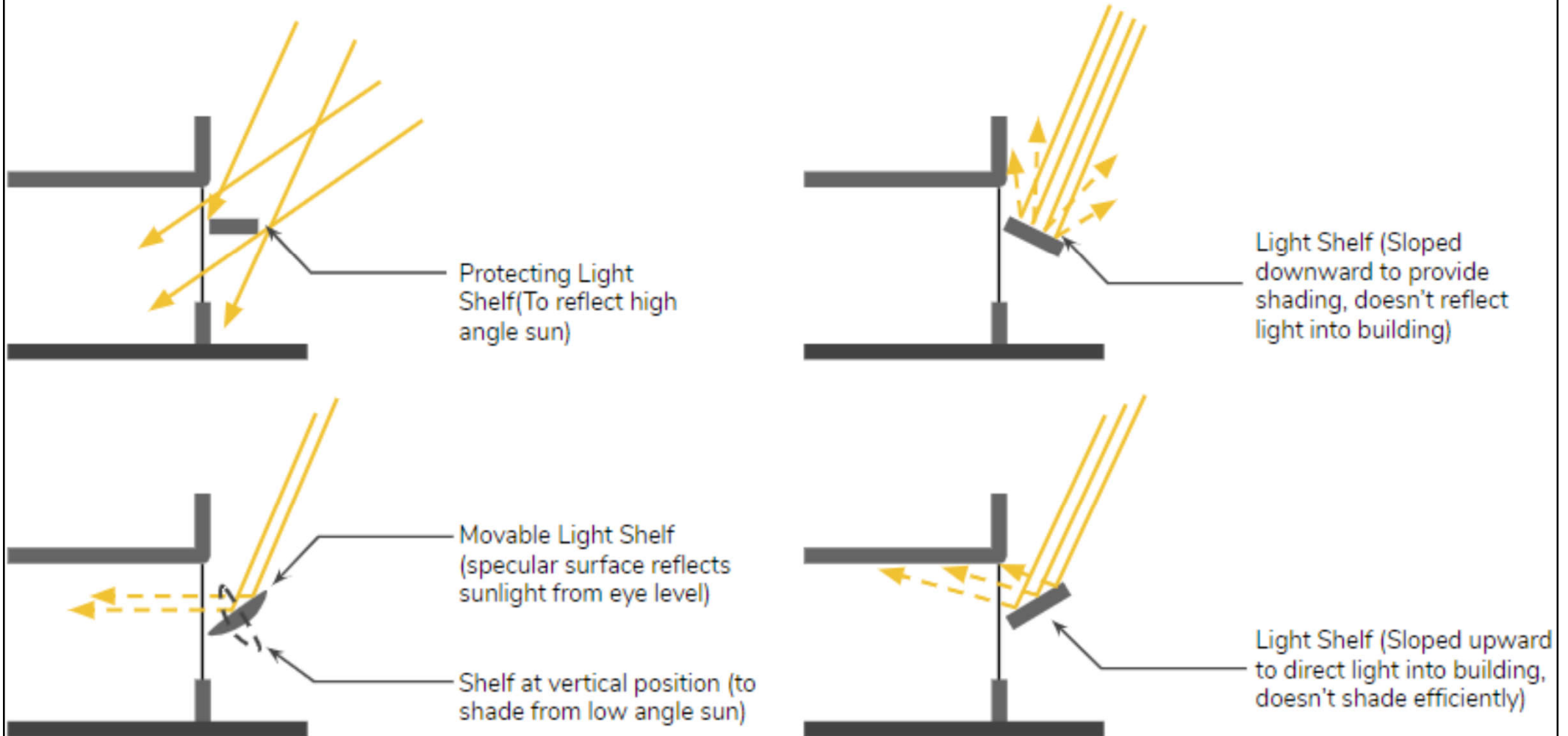
Plan views



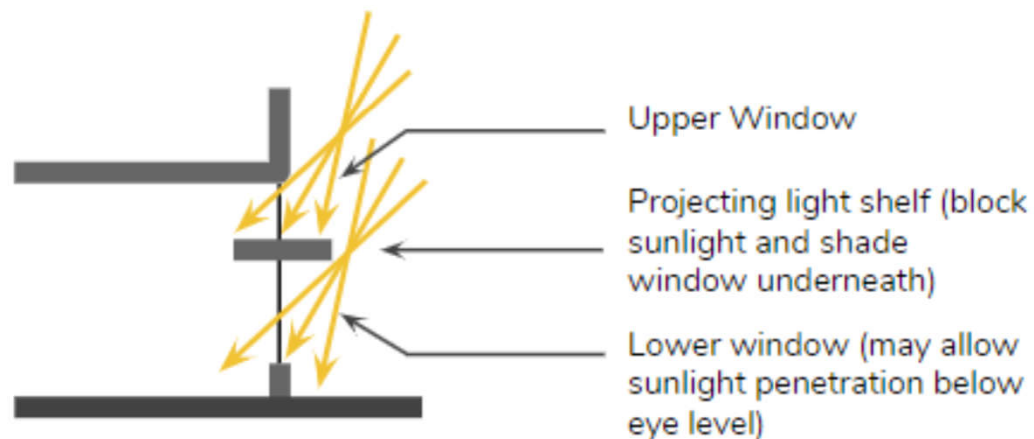
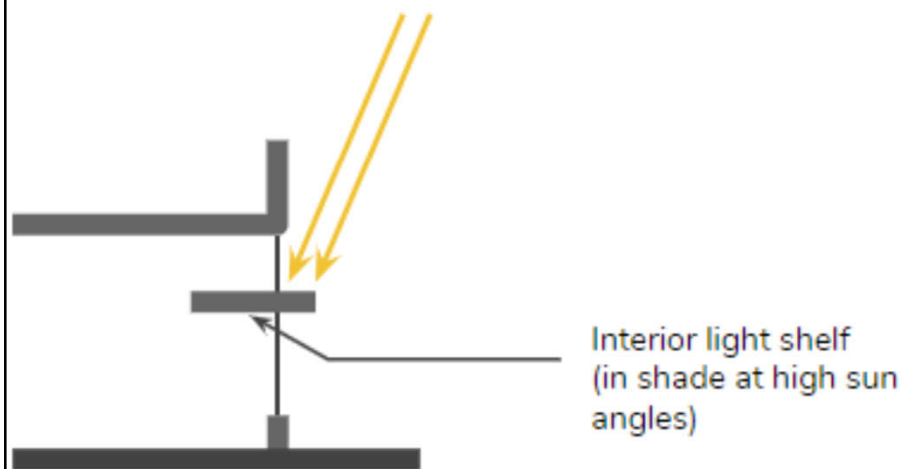
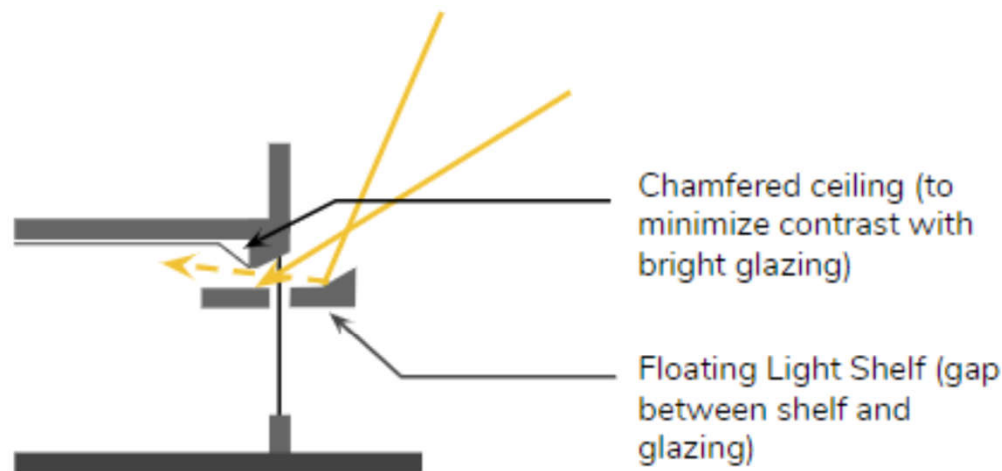
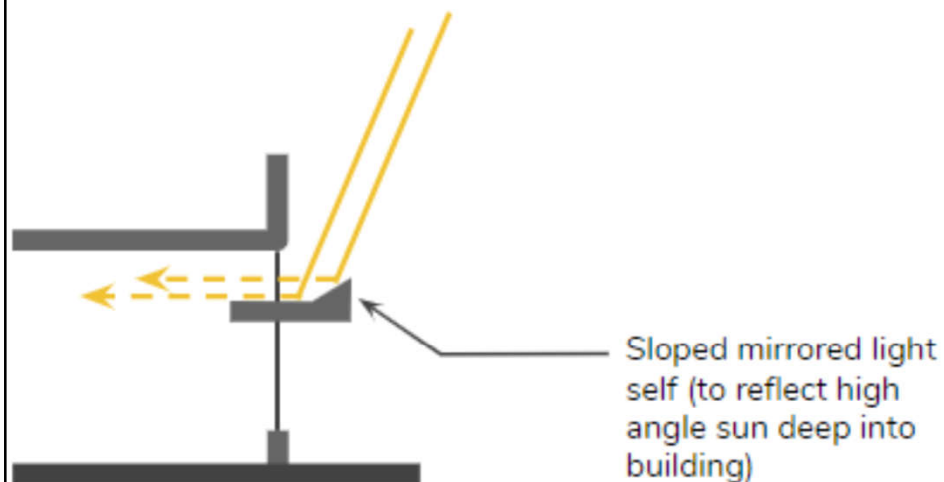
Light shelves for horizontal shading & redirecting



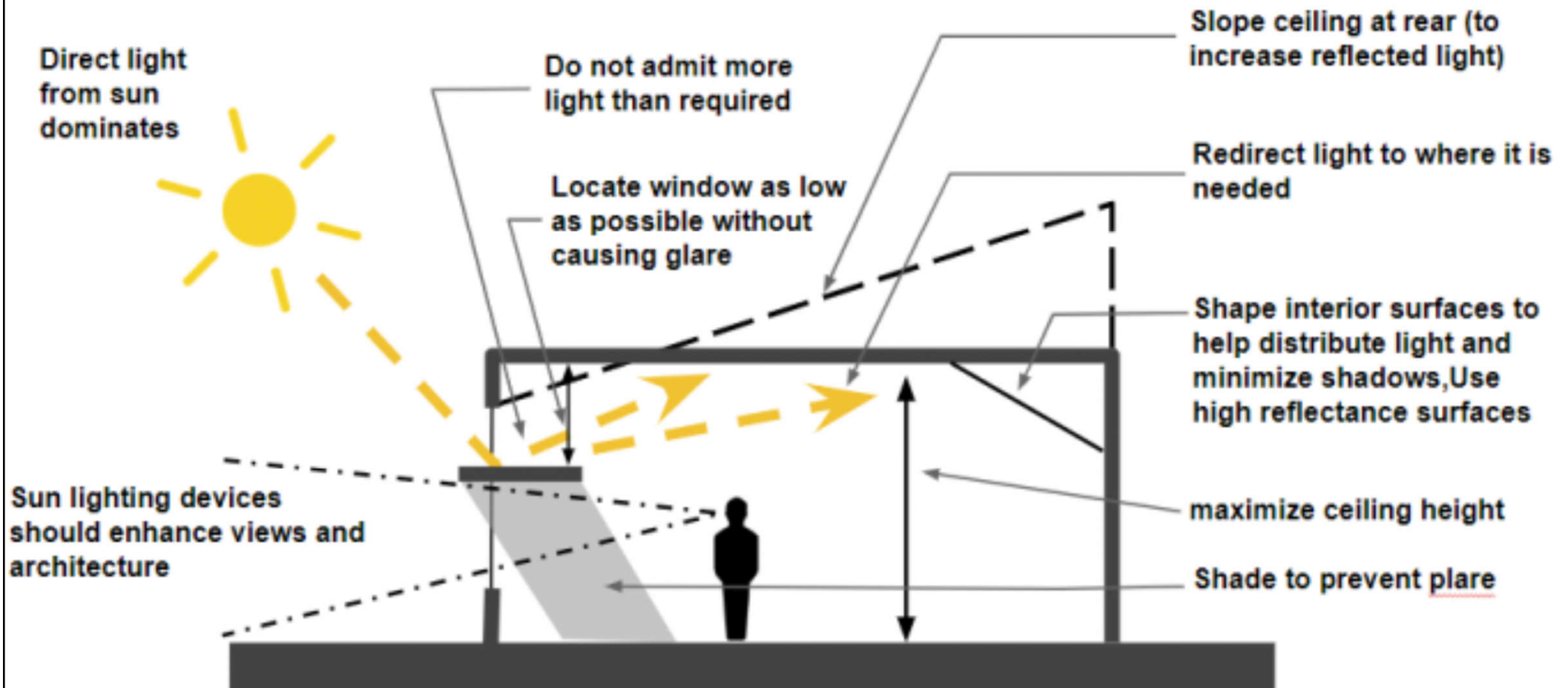
Projecting light shelves provide additional shading for the lower window; sloping the shelves to distribute light



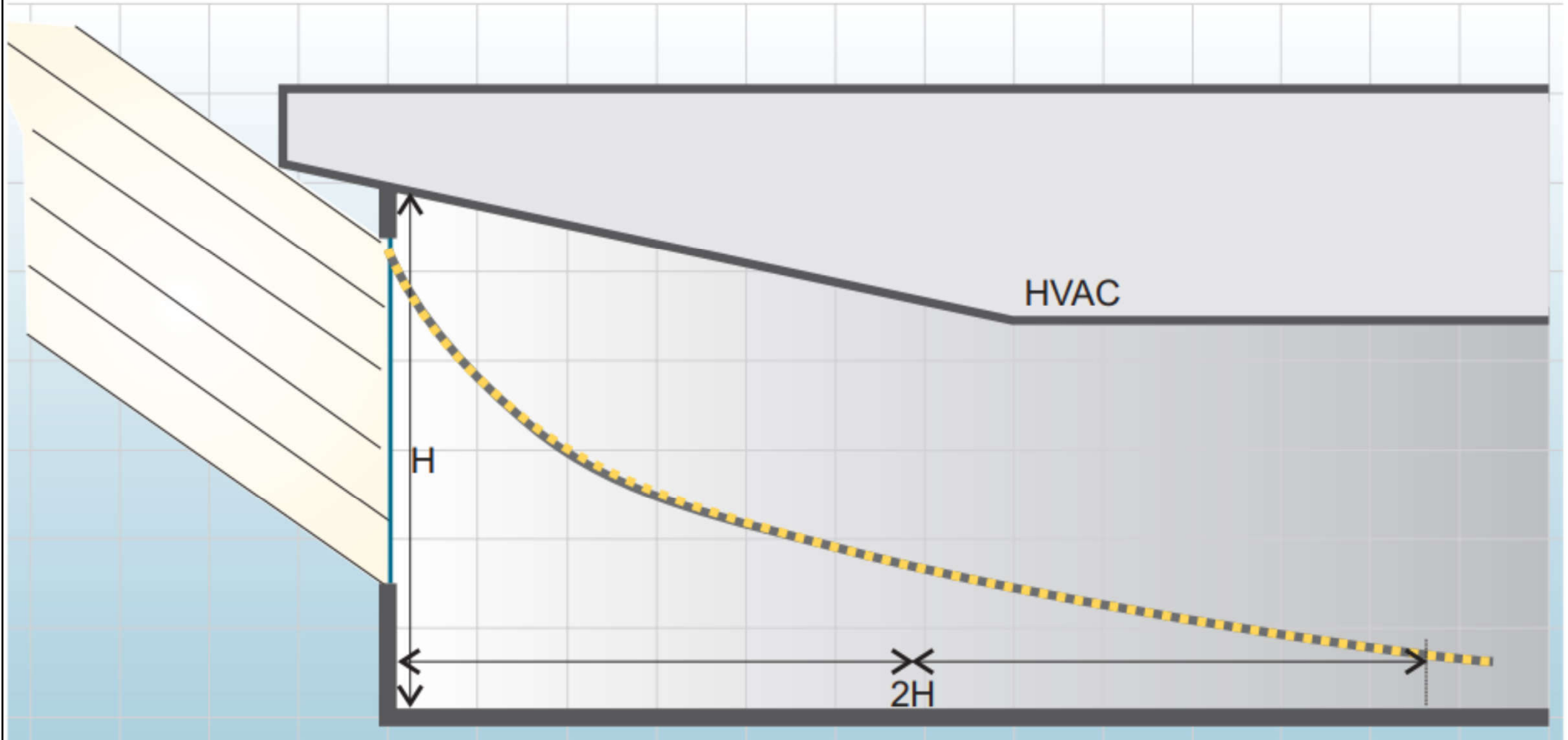
Level light shelf with an inward sloping wedge pushing high angle sunlight more deeply into space



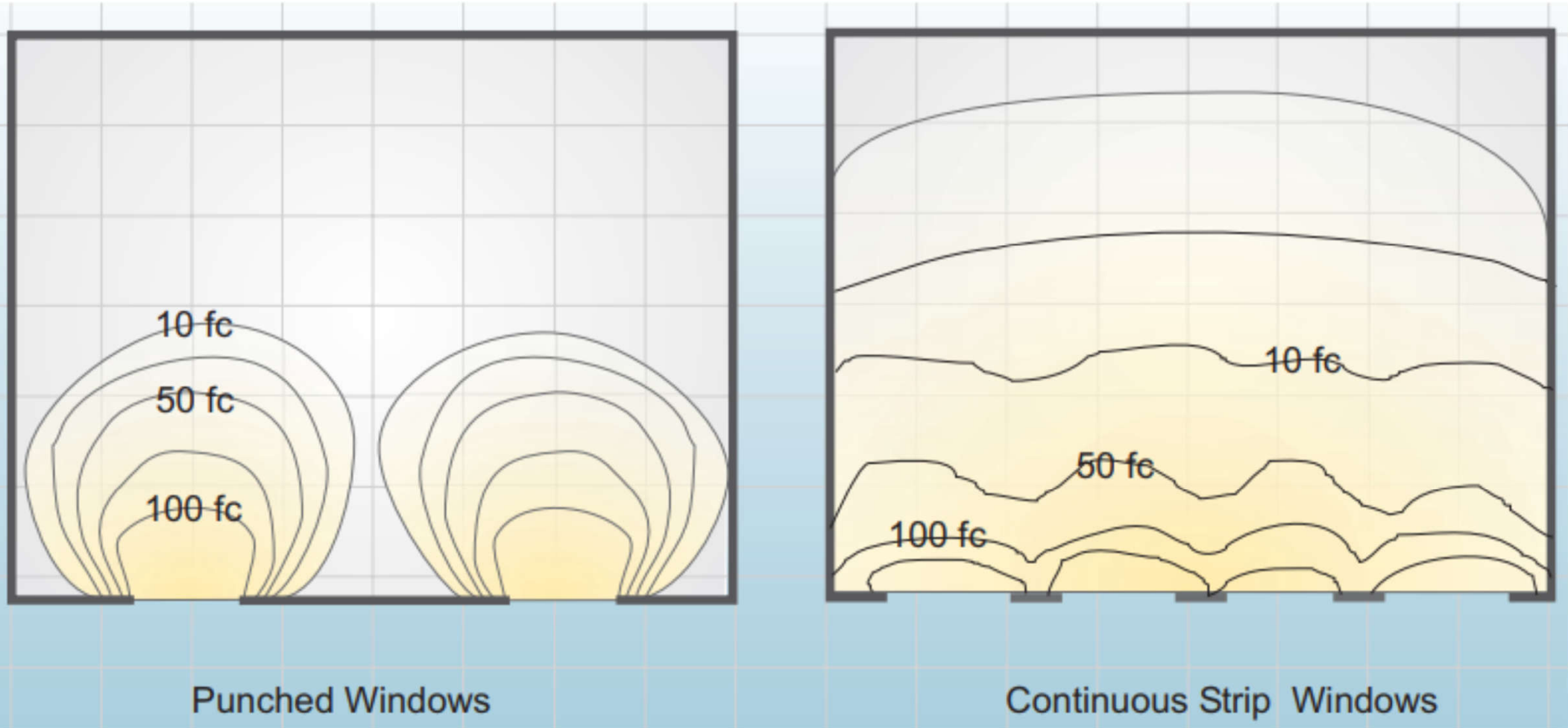
Sunlighting strategies (should be integrated with architecture to use the sunlight indirectly)



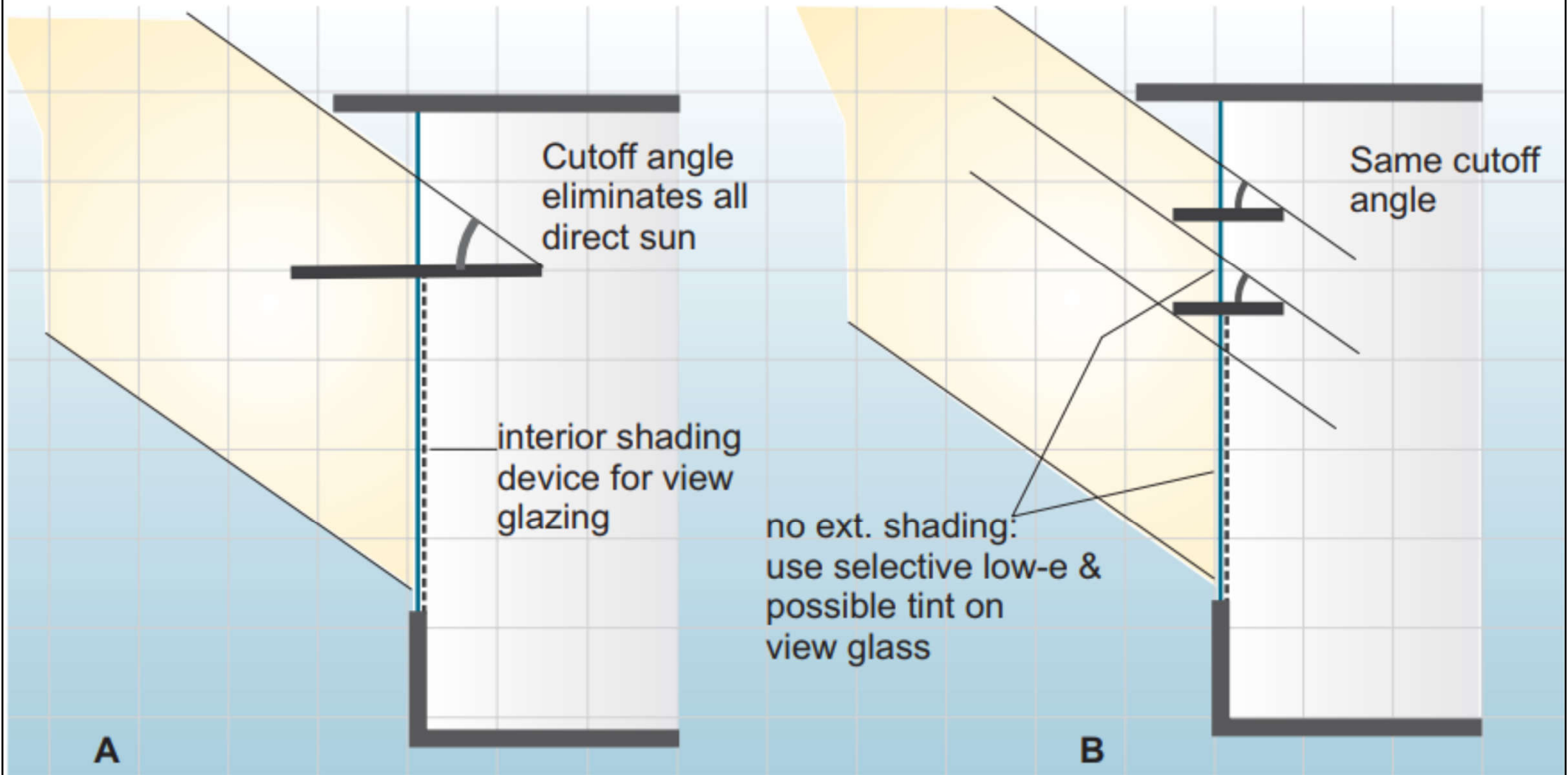
Sidelit building with sloped ceiling at perimeter



Lighting level contours for punched windows & continuous strip windows

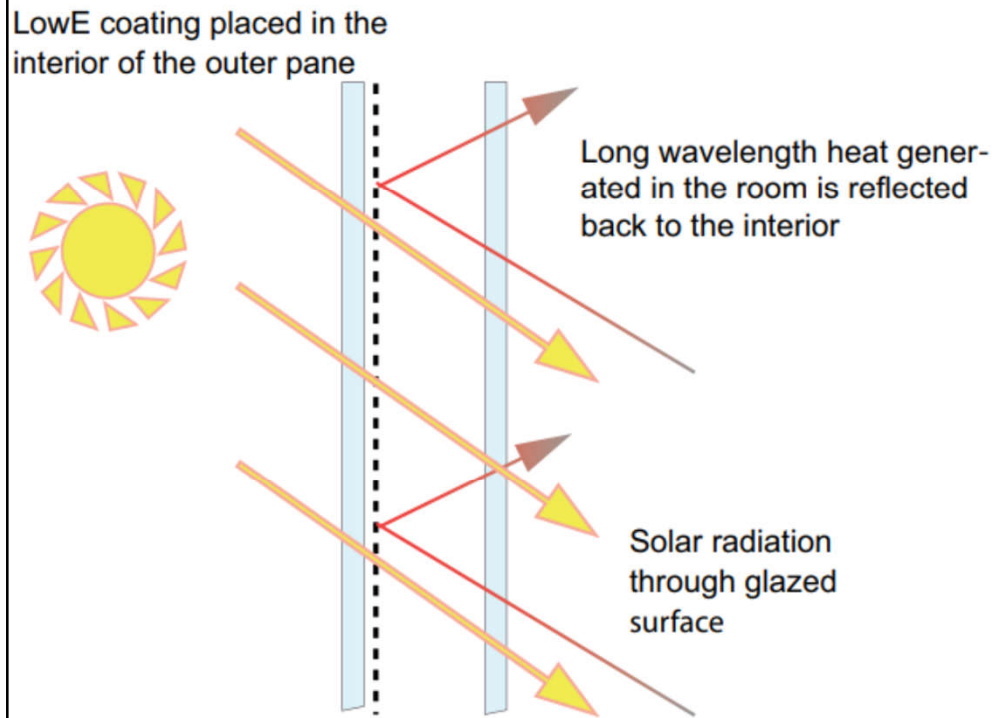


Cut-off angles for light shelf & louvre system

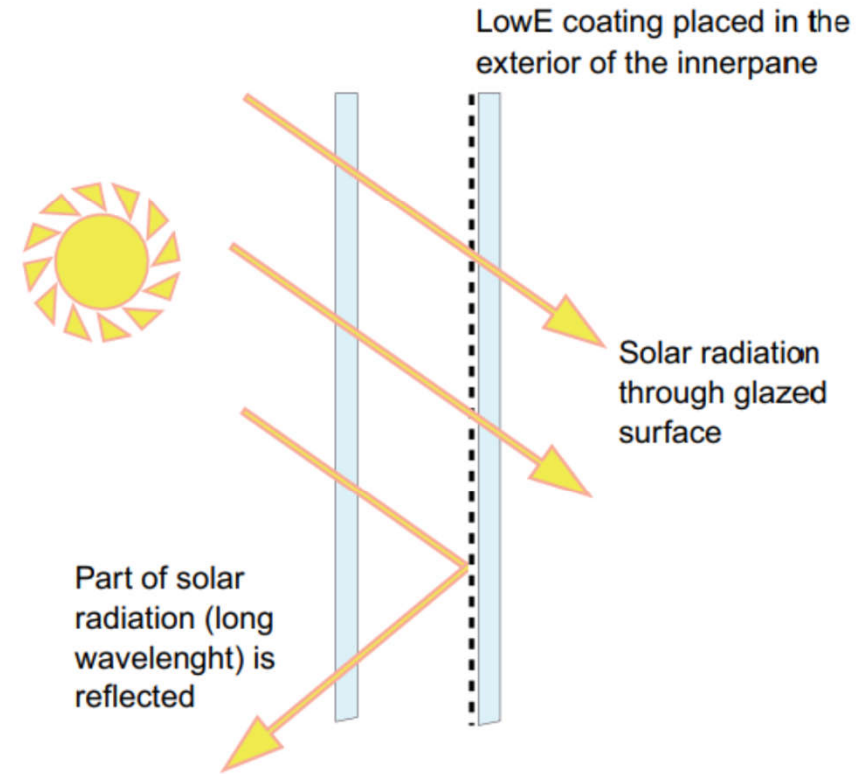


Scheme of low-e coating placement in cold and hot climates

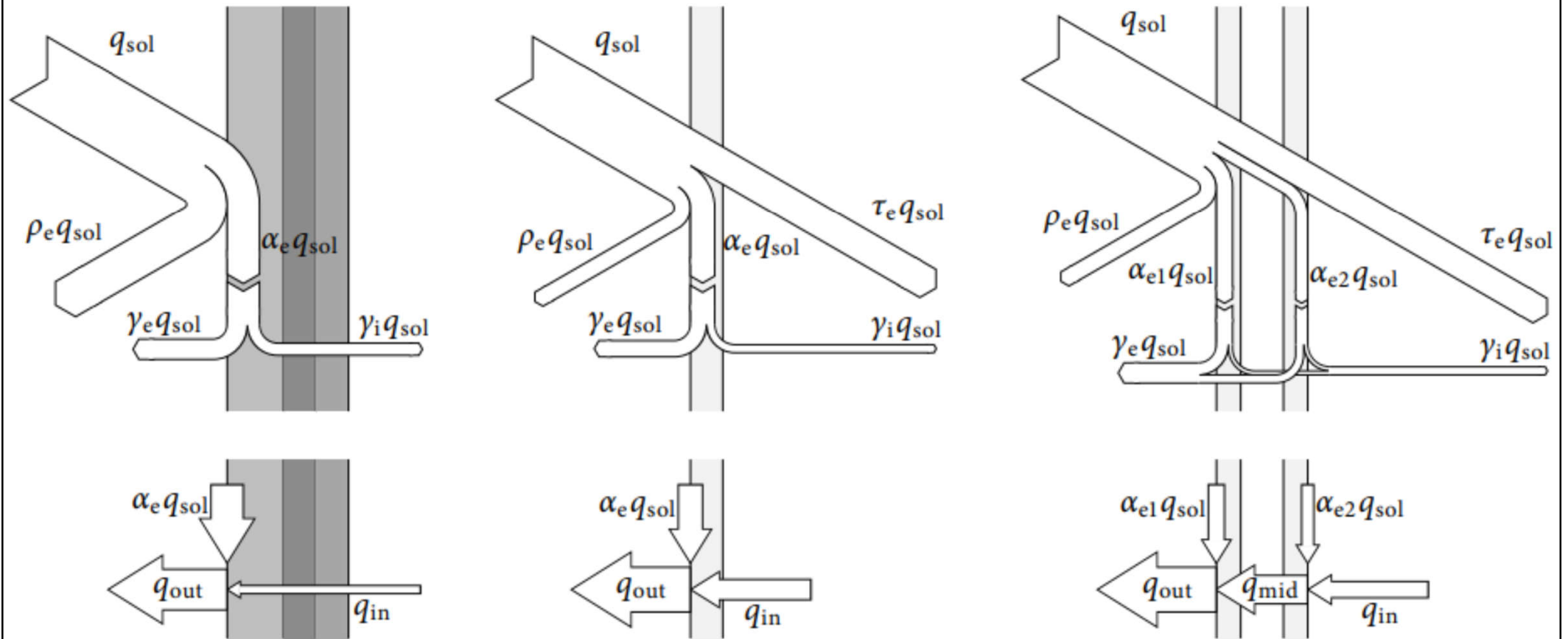
Cold climate: Solar radiation admitted



Hot climate: Part of solar radiation reflected



Solar gains for a non-transparent building element (left), a transparent or single glazed building element (middle) and a double glazed building element (right)

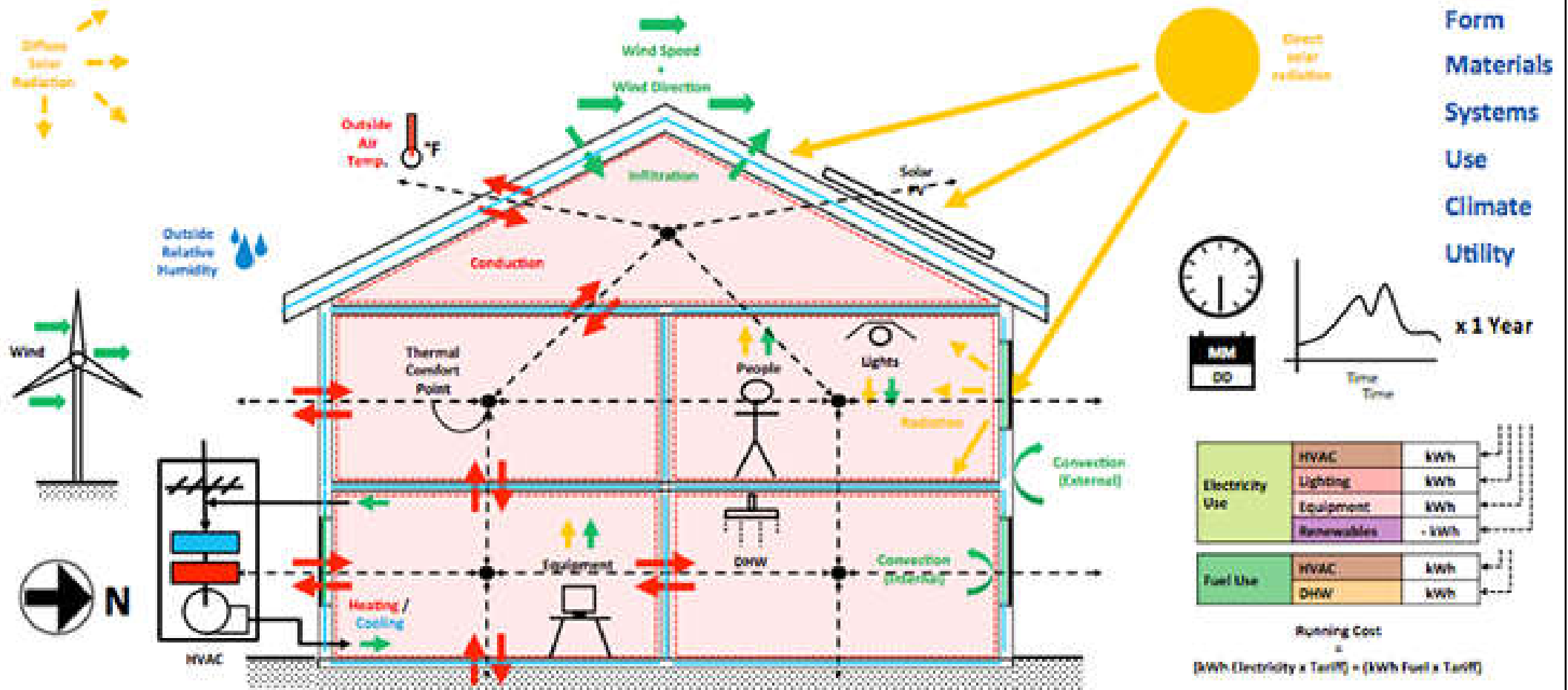


Dynamic simulation

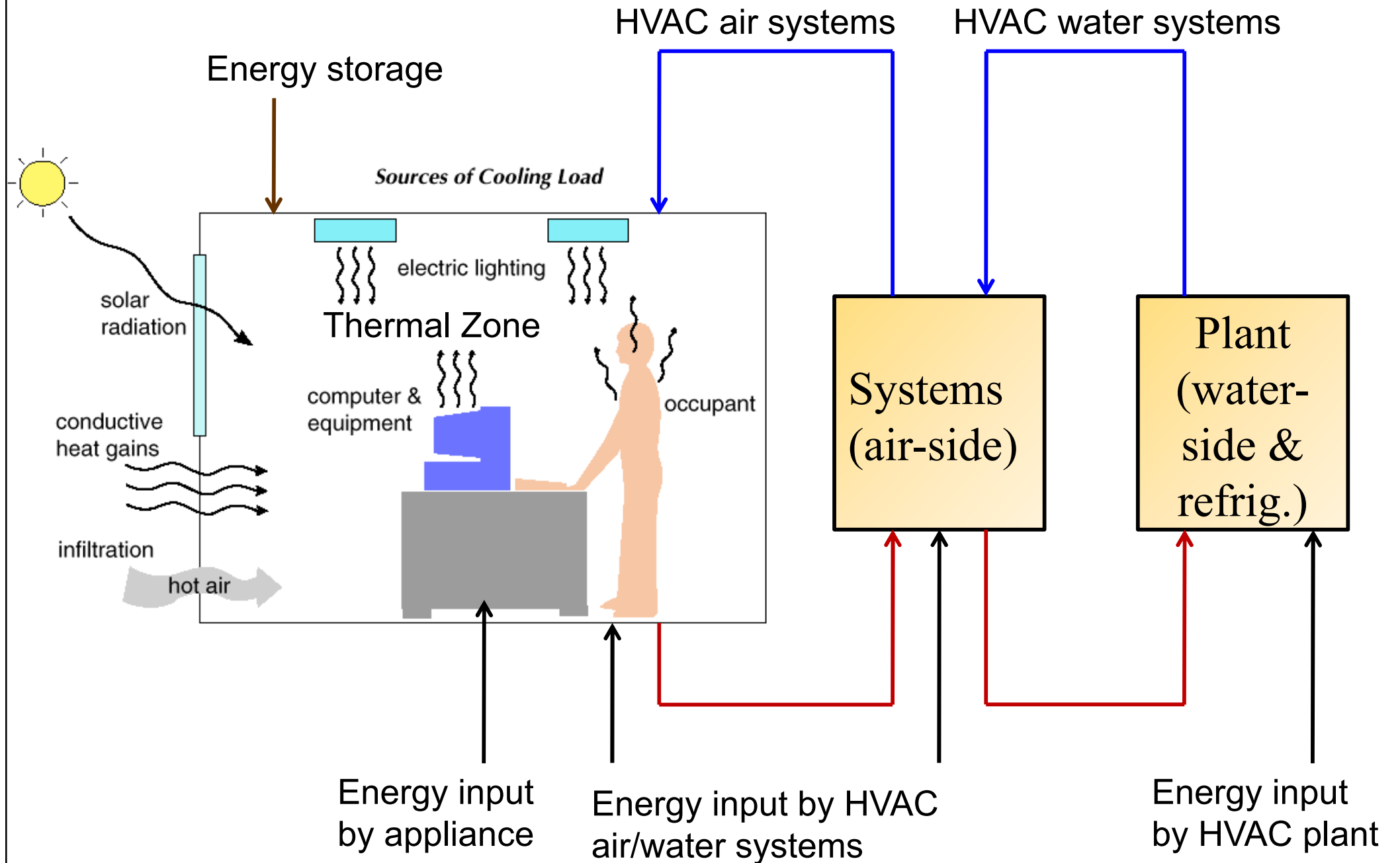


- Dynamic simulation methods
 - Usually hour-by-hour, for 8,760 hours (24 x 365)
 - Thermal & energy calculation sequence:
 - Space or building load [LOAD]
 - Secondary equipment load (airside) [SYSTEMS]
 - Primary equipment energy requirement (e.g. chiller) [PLANT]
- Computer software
 - Building energy simulation programs, e.g. Energy-10, DOE-2, TRACE 700, Carrier HAP

Dynamic whole building energy analysis



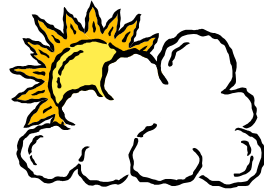
Building energy simulation process



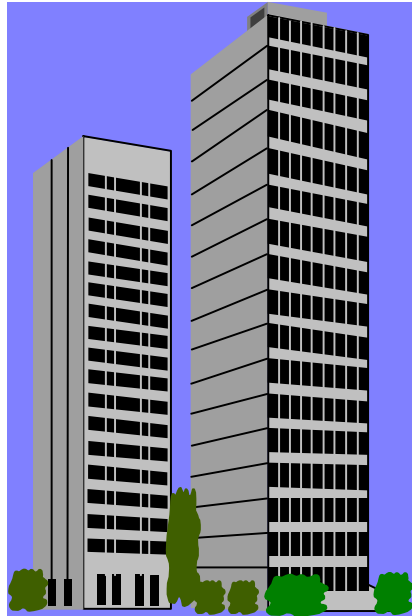
Dynamic simulation



- Building energy simulation
 - Analysis of energy performance of building using computer modelling and simulation techniques
 - Many issues can be studied, such as:
 - Thermal performance (e.g. building fabric, glazing)
 - Comfort & indoor environment
 - Ventilation & infiltration
 - Daylighting & overshadowing
 - Energy consumption/performance of building systems



Weather
data

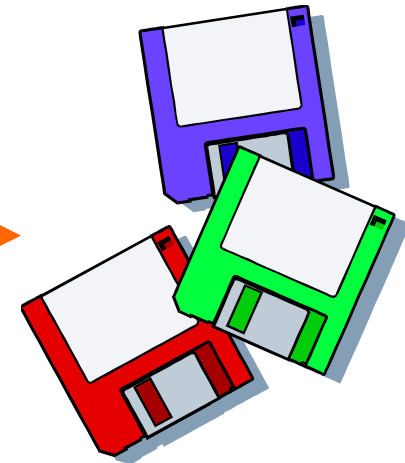


**Building
description**

- physical data
- design parameters

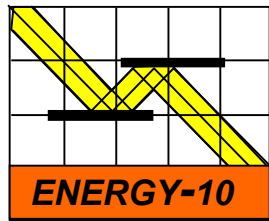


**Simulation tool
(computer program)**



**Simulation
outputs**

- energy consumption (MWh)
- energy demands (kW)
- environmental conditions



blast



DOE-2

Solar-5

ESP-r



ENER-WIN®

Hourly Energy Simulation Program for Buildings

**Building Energy
Simulation Software**



TRNSYS



E-20-II & HAP



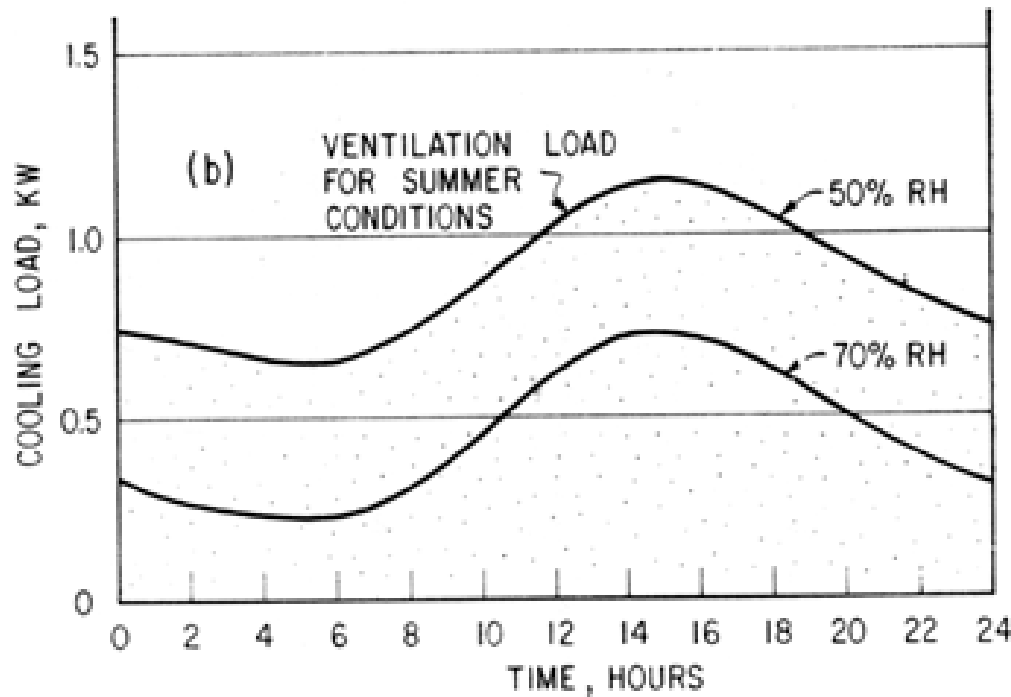
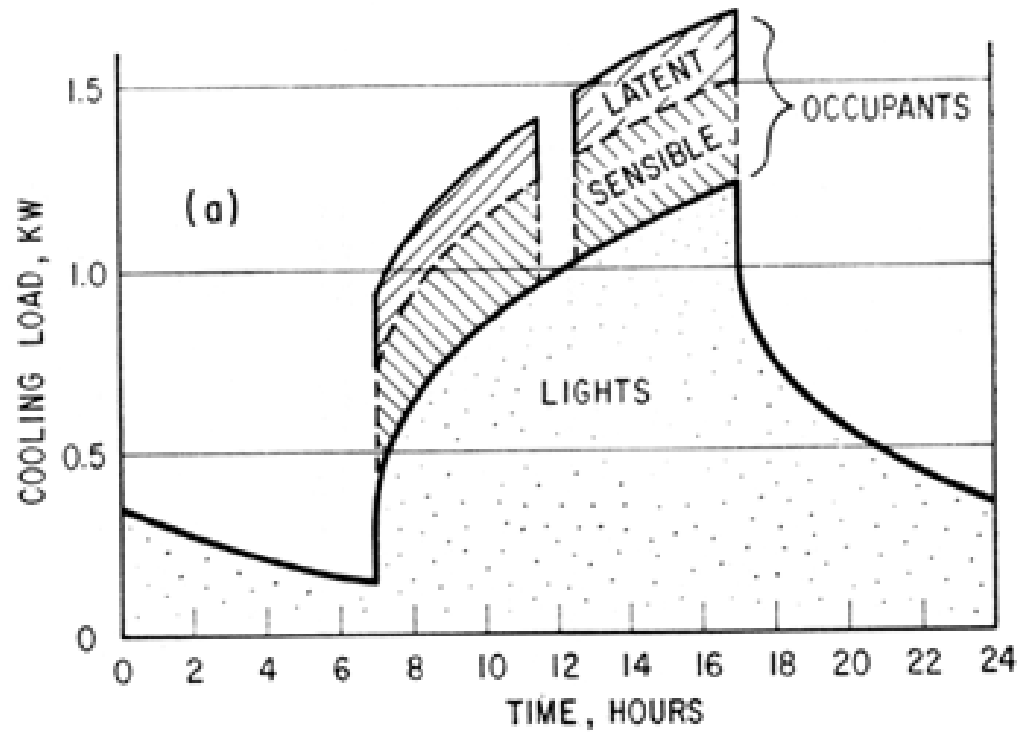
TRANE

TRACE 700

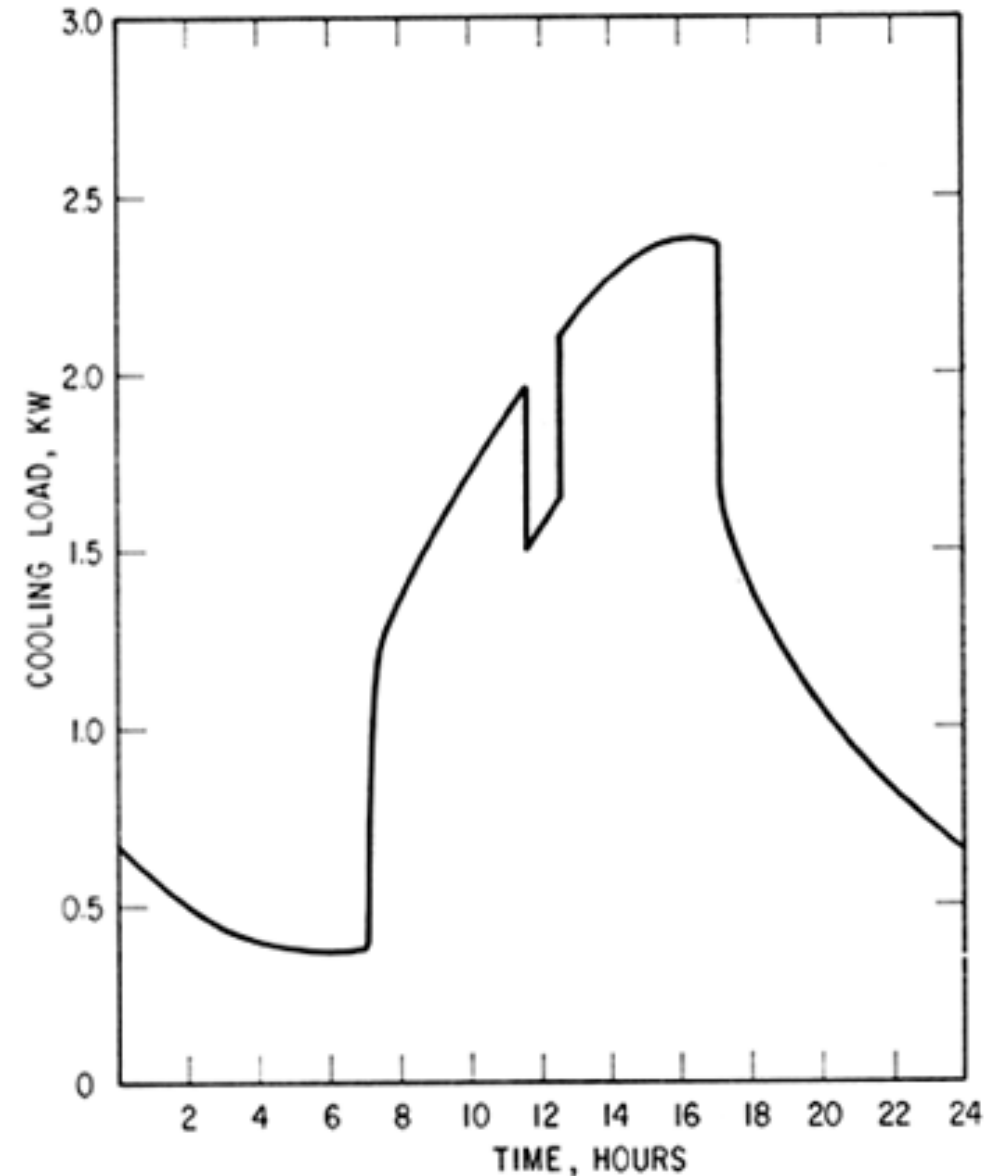


EE4

Cooling load profiles determined from simulation

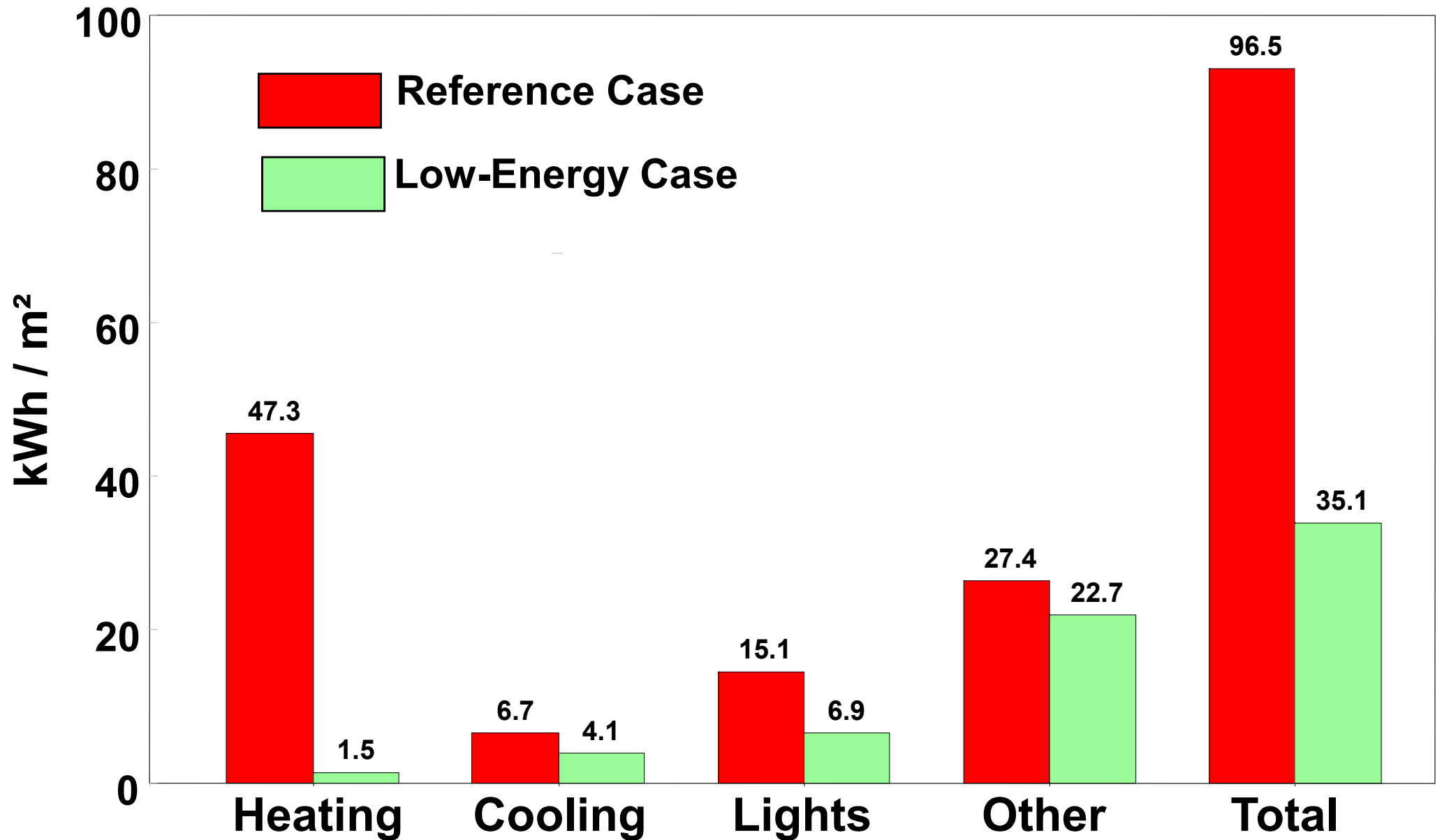


Total cooling load

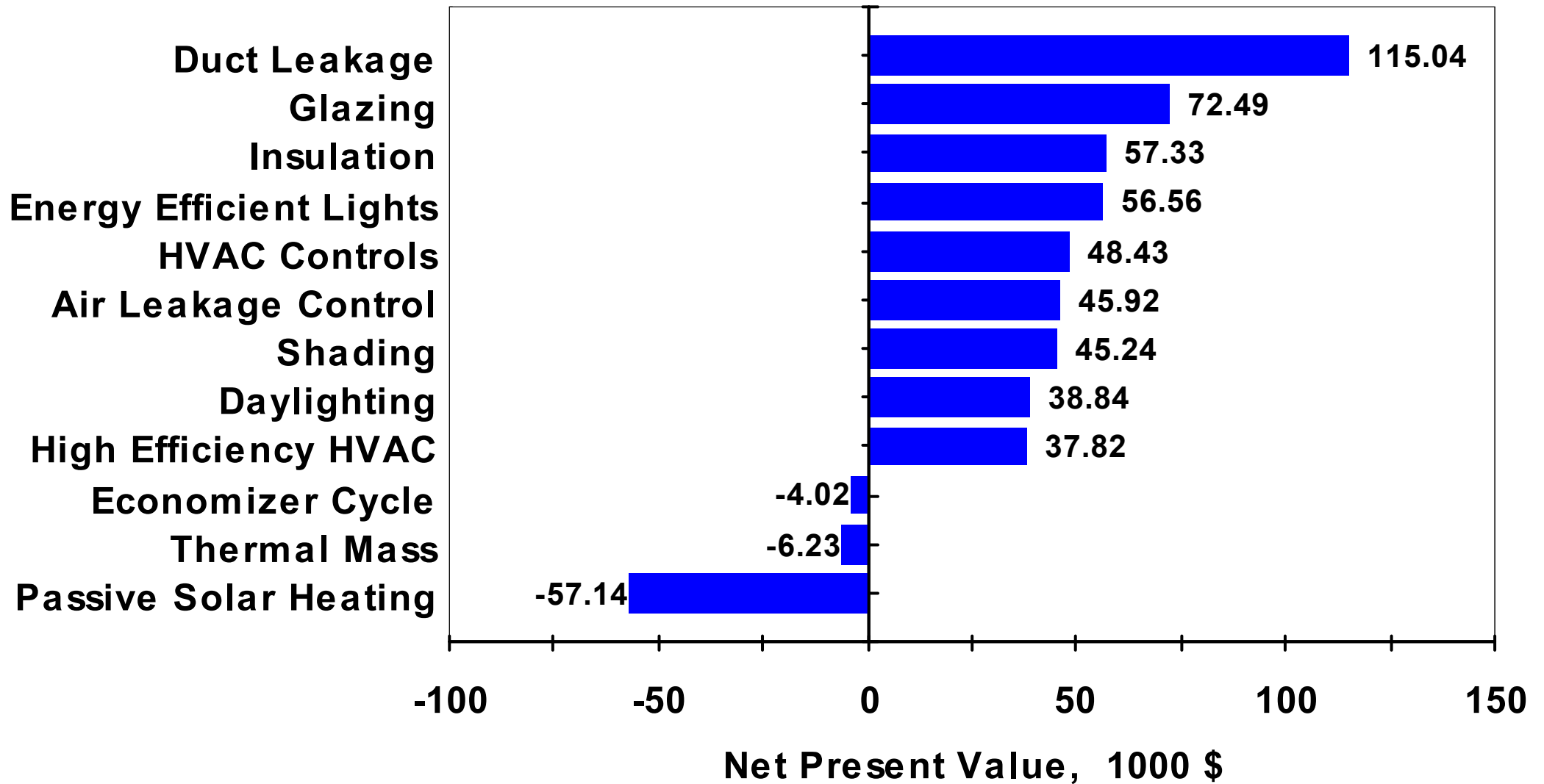


Examples of simulation results for evaluating annual building energy use

ANNUAL ENERGY USE

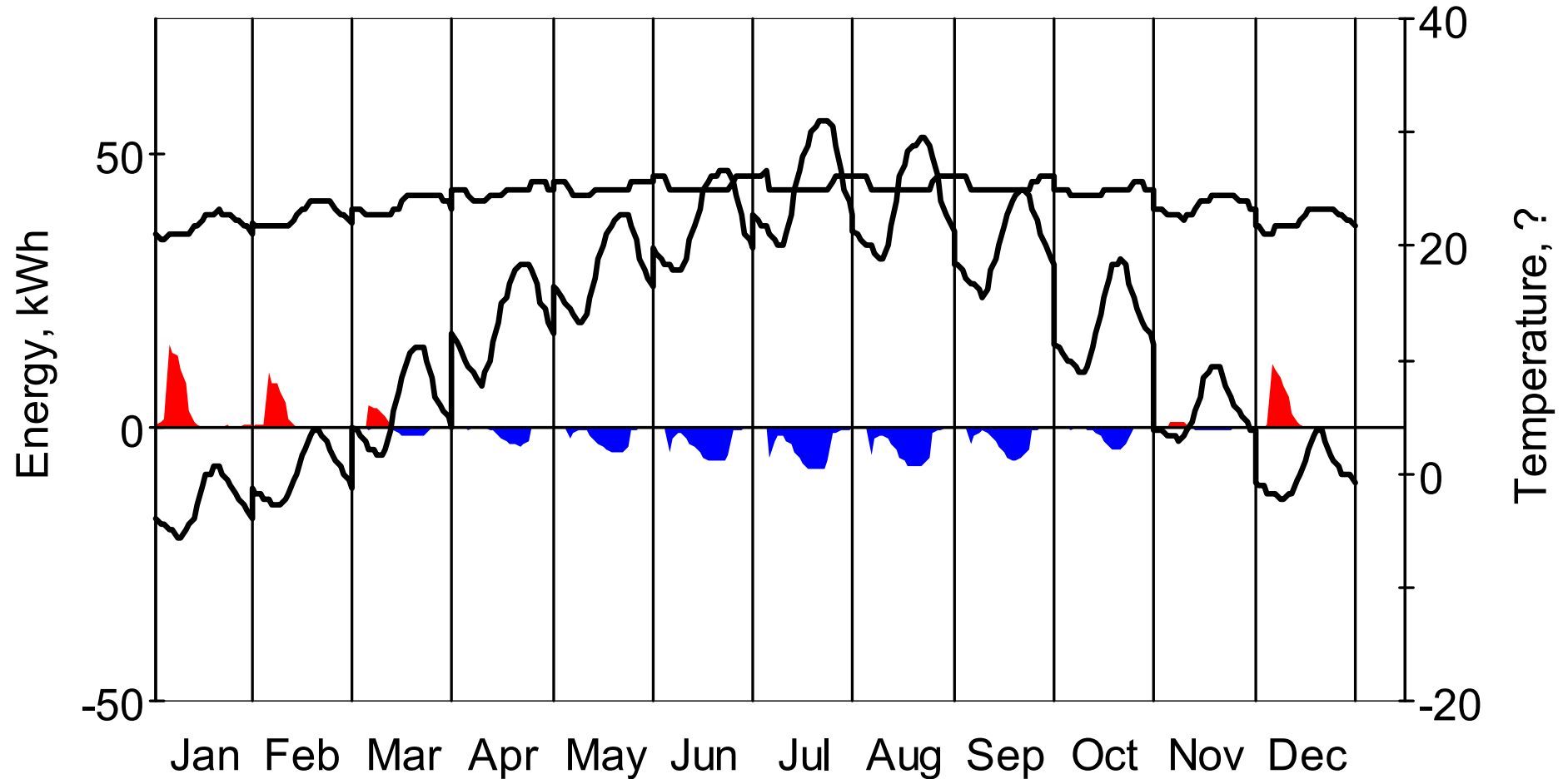


Examples of simulation results for ranking energy efficiency strategies



Examples of simulation results for energy & indoor temperature analysis

Sample - Lower-Energy Case



Average Hourly HVAC Energy Use by Month



Heating



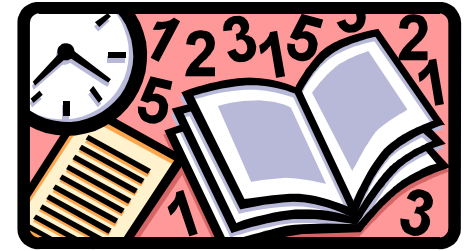
Cooling



Inside T



Outside T



Further Reading

- Module 29: Determining U values for real building elements

<https://www.cibsejournal.com/cpd/modules/2011-06/>

- Passive building design - Design Building Wiki

https://www.designingbuildings.co.uk/wiki/Passive_building_design

- Module 48: Simple thermal analysis for buildings

<https://www.cibsejournal.com/cpd/modules/2013-01/>